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SHIPTRACK DATABASE ANALYSIS

by

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December, 1993

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The radiative characteristics of collected commercial and Navy ship tracks are described through an analysis of AVHRR (Advanced Very High Resolution Radiometer) satellite imagery. The analysis is conducted in a format to show the usefulness of a database approach to processing large amounts of ship track data. 12 cases are analyzed, 9 commercial ship tracks and 3 Navy ship tracks. Satellite imagery for the above 12 cases was collected during the summer months of 1993 off the western coast of the United States. 306 Navy ship reports are associated with 55 satellite images. This data subset was subdivided and cross-referenced to provide statistical data on Navy track formation when a given report was under favorable track formation conditions. Reflectance signatures of the collected tracks show an increase through the first few hours of track formation. The emittance values of the tracks collected from night-time satellite imagery showed the expected decrease as droplet radius decreases. Nuclear powered vessels showed no evidence of track formation. The utility of database analysis for large datasets of observed ship tracks was demonstrated to be a viable method for future analysis of the 4000+ observed ship tracks in the collected imagery.

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SHIPTRACK DATABASE ANALYSIS

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The radiative characteristics of collected commercial and Navy ship tracks are described through an analysis of AVHRR (Advanced Very High Resolution Radiometer) satellite imagery. The analysis is conducted in a format to show the usefulness of a database approach for processing large amounts of ship track data. 12 cases are analyzed, 9 commercial ship tracks and 3 Navy ship tracks. Satellite imagery for the above 12 cases was collected during the summer months of 1993 off the western coast of the United States. 306 Navy ship reports are associated with 55 satellite images. This data subset was subdivided and cross-referenced to provide statistical data on Navy track formation when a given report was under favorable track formation conditions. Reflectance values of the tracks collected from day-time satellite imagery showed an increase through the first few hours of track formation. The emittance values of the tracks collected from night-time satellite imagery showed the expected decrease as droplet radius decreases. Nuclear powered vessels showed no evidence of track formation. The utility of database analysis for large datasets of observed ship tracks was demonstrated to be a viable method for future analysis of the 4000+ observed ship tracks in the collected satellite imagery.

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I. INTRODUCTION

A. OVERVIEW

Conover (196[illegible]) first described the phenomenon of "anomalous cloud lines" seen in TIROS VII visible-wavelength satellite imagery as cloud lines that somehow formed as the result of the passage of a steaming ship. These cloud lines were 25% brighter than neighboring clouds and were up to 500km in length and 25km in width. Conover described these lines as smoke plumes since they were bright and narrow at the formation end and less bright, more diffuse and wider at the trailing end. These cloud lines or ship tracks are readily observable in both visible and infrared satellite imagery.

Analysis of ship tracks and their formation mechanisms have been studied extensively since Conover's initial description. Coakley, et al. (1987) presented the first quantitative analysis of the influence of ships on preexisting clouds and generated considerable interest in this phenomenon. As stated above ship tracks were frequently observed in visible satellite imagery, but ships may affect preexisting clouds in many ways that are observable in the near infrared. In the near infrared clouds are moderately absorbing and droplet size controls cloud reflectance.

Coakley, et al. (1987) described this effect through observations made with the NOAA-9 Advanced Very High Resolution Radiometer (AVHRR) at 3.7 microns. Radke, et al. (1989) and King, et al. (1990) presented measurements from an aircraft in a ship influenced cloud that showed that microphysical effects were important in the formation of ship tracks. Coakley, et al. (1987) reported that under stable meteorological conditions ship-stack exhaust enhanced cloud reflectivity at 3.7 microns. The emissions from a conventionally powered ship served as a source of cloud condensation nuclei (CCN) that increased the number of cloud drops and, more importantly, reduced the average droplet size. At 3.7 microns, the ratio of scattered radiation to absorbed radiation reduces to 1/r, r being the droplet radius. The scattering cross section of a droplet is proportional to its geometric cross section and the absorption cross section is approximately proportional to its volume. Thus the ratio of scattering to absorption increases as droplet radius decreases.

Porch, et al. (1990) and Hindman (1990) argued that the dynamical effects of the ship's motion play an important part in the formation of ship tracks. A portion of this study will focus on these findings.

B. BACKGROUND

1. Shiptracks

Shiptracks form primarily during the summer months but have been observed at other times throughout the year. Areas most prominent in ship track formation are the eastern ocean basins, more specifically, the North Eastern Pacific Ocean basin which has been studied extensively with respect to ship track formation. Figure 1 shows shiptrack formation off the southern California coast. Channel 3 (3.7 microns) reflectance is a function of droplet radius. Shiptrack reflectance is primarily a function of droplet radius therefore, channel 3 will provide the best measure of track reflectance. Current theory suggests that ship tracks form in a shallow layer of convection topped by a stable layer within a subtropical high pressure region. The marine boundary layer is well-mixed and capped by stratus or stratocumulus clouds.

2. Cloud/Track Formation Mechanisms

Cloud formation mechanisms are well understood, while shiptrack formation processes are not as well understood. Understanding this process is important because the phenomenon was addressed by Coakley et al. (1987) as an example of the possible global impact of anthropogenic particles on clouds. Twomey, et al. (1984) estimated that if the increase in man-made aerosols is taken as being proportional to that for carbon dioxide, the effect of the aerosols on the earth's

radiation through their interaction with clouds would be comparable in magnitude but opposite in sign to that of increased carbon dioxide.

Cloud droplets condense when the atmosphere becomes supersaturated with respect to water. This supersaturation is

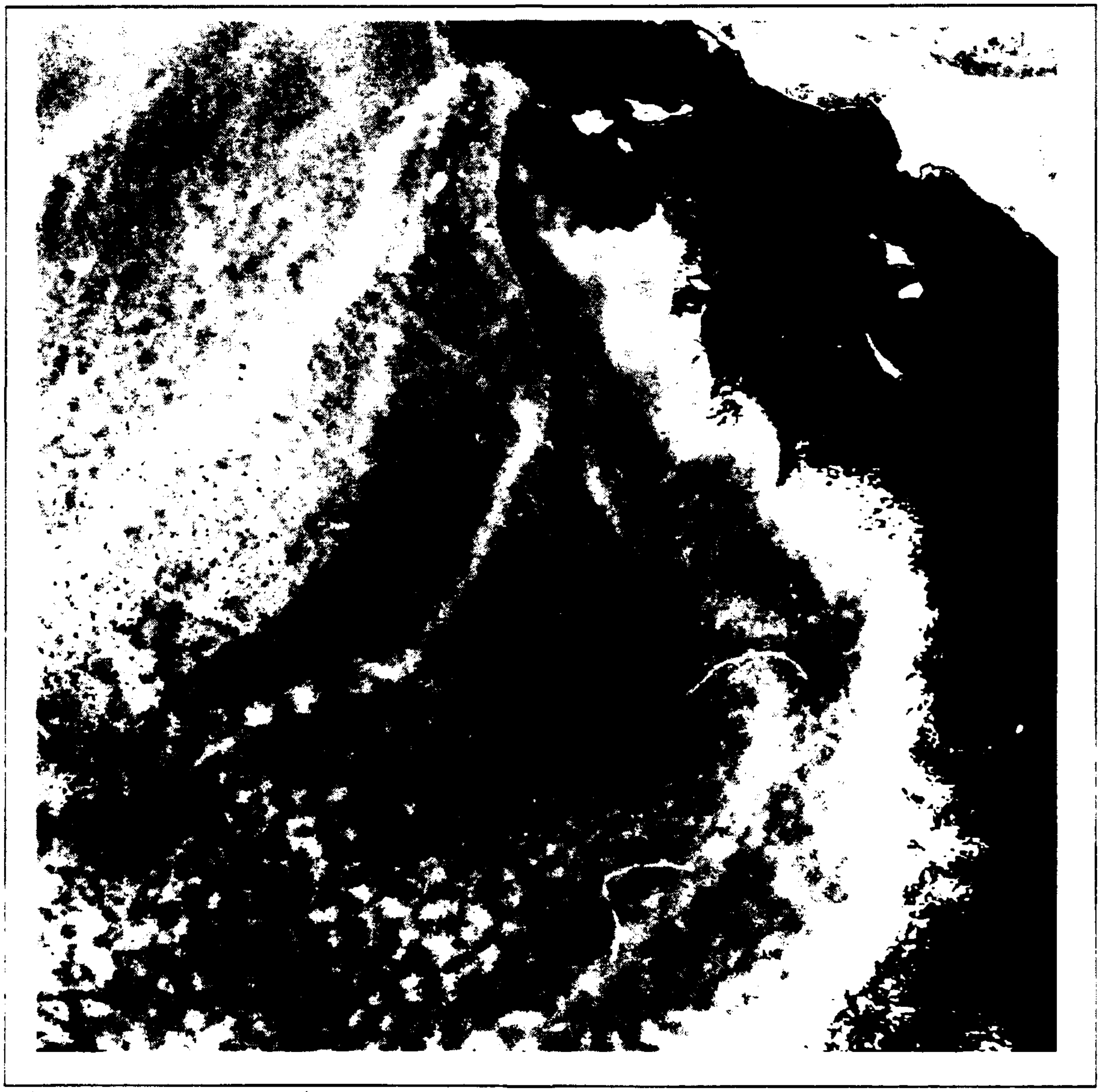

Figure 1. Satellite Imagery of Ship Tracks at 3.7 μm.

caused by cooling saturated parcels adiabatically, radiative cooling or cooling by conduction. Cloud droplet concentration depends on the number of CCN present and the maximum supersaturation achieved. Hindman (1990) reported that if the supersaturation attained were 0.1%, then approximately 20 droplets per cubic centimeter would form. If the supersaturation were 1.0% then approximately 100 droplets would form. Additionally, the magnitude of supersaturation is driven by the rate of cooling of the air. Increased values of supersaturation implies increased numbers of cloud condensation nuclei for the typical maritime CCN spectrum.

As conventionally powered ships (and possibly nuclear powered vessels) transit the oceans they introduce into the atmosphere aerosols and particulate matter in the form of CCN. These ships also produce heat, momentum and moisture. The question has been to try and determine what combination of these products produces the unique characteristics of shiptrack clouds or if just a single variable is responsible for their formation.

Monahan, et al. (1986) reported that the particulates produced by ships are either sub-micron combustion particles or low concentrations of micron size spray particles. Twomey, et al. (1968) reported that supersaturation of greater than 0.5% was required for cloud droplet formation. Radke, et al. (1989) showed that only 10% of the total particulate matter as a result of combustion served as CCN for the formation of

shiptracks, and that the liquid water content was unexpectedly high. Therefore, aerosols/particulate matter introduced into a supersaturated atmosphere as a result of combustion can serve as CCN for droplet formation.

If we assume that the CCN spectrum is given as in the Radke (1989) experiment, then an ambient cloud droplet concentration of approximately 40 cm^{-3} would result from a supersaturation of 0.1% and a shiptrack droplet concentration of 110 cm^{-3} results from an supersaturation of 1%. Hindman (1990) reported that only a portion of the ship produced CCN is required to account for the increase in cloud droplet concentration.

As mentioned above, ships transiting the oceans produce heat, momentum and moisture. Porch, et al. (1989) reported that the heat emitted from a conventionally powered ship's stack might lead to the enhancement of an existing cloud as a result of the updraft and provide for an increased value of supersaturation (%). This might explain the high levels of liquid water content observed by Radke, et al. (1989). As a ship moves across the ocean it disturbs the marine boundary layer. It's momentum or air wake can produce additional upward vertical motion which could lift aerosol/particulate matter, specifically, CCN, or enhance an existing cloud through updrafts.

Hindman (1990) examined the moisture content in the shiptrack formation process and reported that stack gas mixing

ratios of 280 g/kg at 180°C or 475 g/kg at 300°C should lead to track formation. Moisture above a certain level can lead to increased values for supersaturation (%) and the mixing of hot, moist stack gas with marine boundary layer (MBL) air should lead to the formation of a shiptrack type cloud if the moisture content of the stack gas is large enough.

C. RADIATIVE EFFECTS

As electromagnetic radiation enters the earth's atmosphere it is attenuated. This attenuation can be in the form of scattering or absorption. Absorption dominates through most of the thermal IR region of the atmospheric spectrum and attenuation of short wavelength radiation is driven by reflection due to aerosols, water vapor, clouds and air. These constituents interact differently with incoming radiation and their interactions can be characterized as either absorption or scattering. The appropriate interaction in a study of shiptracks is reflectance through scattering for satellite imagery collected in the daylight hours and emittance of absorbed radiation for satellite imagery collected during the evening or early morning hours.

Scattering of incident radiation by a cloud mass is dependent upon several factors but those of concern in this work are particle size distribution and composition. Scattering by particles comparable in size to the incoming

radiation wavelength (Mie scatter) is the primary mechanism of interaction.

The amount of scattering and subsequent reflectance is a function of both size and concentration of the scatterers. At 3.7 μm reflectance dominates with minimal absorption and is a function of particle size only. Aerosols in the lower atmosphere vary in size from a few tenths of a micron in radius to hundreds of microns. The AVHRR channel 3 reflectance (centered at 3.7 μm) provides the best measure of shiptrack reflectance.

Emittance of absorbed radiation is also a function of droplet size and concentration. With decreasing droplet size emittance decreases. Emittance (ϵ) is related to reflectance through the formula

$$\epsilon = 1 - \rho \quad (\rho = \text{reflectance})$$

with transmittance equal to zero. Therefore, if cloud reflectance changes emittance changes. Kuciauskas, et al. (1993) have shown that shiptracks are detectable in night-time satellite imagery in the near infrared at 3.7 microns.

D. THESIS OBJECTIVE

The objective of this thesis is three-fold. The overall focus of this research is to demonstrate the utility of analyzing shiptrack data using a relational database. Figure 2 is an example of some of the possible fields to be included in this database. Large numbers of ship tracks have been

observed in the collected satellite imagery. These shiptracks have many characteristics in common. Commercial shiptracks appear as curvalinear cloud features sometimes extending for hundreds of kilometers. Their formation mechanism is not completely understood and envolves many complex factors such as environment, ship type and propulsion type. Additional fields of the database will include sections relating to meteorological data and image analysis data specifically, sounding data, inversion strength, sea surface temperature, ambient air temperature, and boundry layer height. Also included will be fields containing statistical data on average track reflectance and emittance values, average ambient reflectance and emittance values, and temperature data for both track and the surrounding ambient atmosphere. Given the large amount of data available, database analysis is a viable approach for future research in determining the shiptrack formation mechanism. The second objective is to locate, observe and describe the spatial and radiative characteristics of shiptracks off the western coast of the United States. This search will include a dedicated analysis of collected satellite imagery trying to identify shiptracks produced by U. S. Navy vessels operating in the various target areas. A third goal is to enlarge the dataset of collected and analyzed commercial shiptracks.

Chapter II will outline the approach of the study and describe the data collection and analysis. Chapter III will be

a discussion of the results on a case basis and Chapter IV will present conclusions and make recommendations for additional study.

II. METHOD

A. OVERVIEW

Some of the previous thesis work with shiptracks has focused on associating a shiptrack with a specific ship and ship type (Pettigrew 1992), comparing the radiative characteristics of tracks formed in differing ocean basins (Millman 1992), and studying shiptracks as they transit through different cloudiness transition regions (Evans 1992). The focus of this study is in part to continue the previous research in hopes of expanding our overall understanding of the spatial and radiative properties of shiptracks and to attempt to answer some of the outstanding questions with respect to shiptrack formation. More specifically, do U. S. Navy vessels produce shiptracks given a marine boundary layer conducive to their formation and what are the propulsion plants associated with these tracks? Given the appropriate meteorological conditions, "Will a nuclear powered vessel produce a shiptrack?"

B. DATA

The data utilized for this study are from the Advanced Very High Resolution Radiometers (AVHRR's) onboard the NOAA-10/11/12 satellites. These satellites are polar orbiting at approximately 860 kilometers above the earth's surface. The

AVHRR continuously records 2048 samples per scan line centered on nadir. The instrument senses upwelled radiation, both emitted and reflected energy, over five wavelength channels centered at 0.63, 0.86, 3.7, 11.0, and 12.0 microns. At nadir, this geometry produces a pixel resolution of approximately 1 km by 1 km.

The primary data source used in this analysis was satellite imagery collected during May/June/July/August 1993 off the western coast of the United States. The data were analyzed on a Sun Microsystems SparkStation 2 and SparkStation 10 using the Terascan image processing software package. A channel 3 subscene of the target area is first created in the search for shiptracks. After the tracks have been located the shiptracks are digitized and additional subscenes are created. A brief description of these additional images follows:

LOW1 - channel 1 albedo scaled by the solar zenith angle and low cloud asymmetric reflectance factor (%).

LOW3 - channel 3 albedo scaled by the solar zenith angle and low cloud anisotropic reflectance factor (%).

S12A - the ratio of channel 1 albedo to channel 2 albedo (1.0 to 3.0)

TMP4 - channel 4 brightness temperature (K).

T45 - difference between channel 4 and channel 5 brightness temperature (K).

These subscenes serve as the input files for the shiptrack extraction algorithm.

C. SHIPTRACK EXTRACTION ALGORITHM

A modified version of the Nielsen and Durkee (1992) algorithm was used to extract shiptrack data from satellite passes. The algorithm will automatically identify shiptracks with minimal user intervention but, the modification allows one to select specific shiptracks for further analysis. Once a track has been identified for analysis it is digitized and processed by the algorithm.

The algorithm extracts a 61 km swath of data along the entire length of the shiptrack from a given 1000 km by 1000 km image file. This image file contains the five products mentioned above which have been registered such that each pixel is 1 km by 1 km. This extracted data contains the radiative signature of the shiptrack and the surrounding ambient cloud mass. The algorithm outputs a separate binary data file for each of the product subscenes described above.

Prior to any averaging methods or statistical treatment the linearized records file of the shiptrack must be transferred to a 1 km x 1 km grid to ensure constant pixel size throughout the width and length of the shiptrack. This correction is necessary to account for the AVHRR's scan

geometry and the curvature of the earth. At nadir, pixel resolution is approximately 1.1 km by 1.1 km spaced approximately .9 km apart. This resolution decreases as you move horizontally left or right from the center pixel. At the edge of the extracted data file the pixel resolution is approximately 2.4 km along-track and 14.7 km across-track.

In applying the algorithm, some smoothing of the data is realized but the shiptrack and surrounding cloud mass essentially retain their radiative and spatial characteristics. These files can then be examined to determine the radiative characteristics of the shiptrack and the surrounding atmosphere.

D. ANALYSIS

The algorithm processes each image file by determining the location of the shiptrack in the satellite image. After the extraction algorithm is complete, a statistical analysis of the radiative characteristics of the shiptrack and surrounding ambient cloud mass can be performed. The analyzed statistics include: average ambient cloud and track albedo in the visual and infrared channels, an average of the ratio between channel 1 and channel 2 albedo for both ambient cloud and track, ambient cloud and track brightness temperatures, and average difference in brightness temperatures for both ambient cloud and track in channels 4 and 5.

Also included in these statistics are the per cent change between cloud and track for the visual and infrared channels, the channel 1 and channel 2 ratio, the channel 4 brightness temperature, and the difference in channel 4 and channel 5 brightness temperatures.

Greater than one hundred twenty satellite images were examined for the presence of Navy and commercial shiptracks. The satellite imagery was collected at all times throughout the day from NOAA 10, 11, and 12. The satellite data ranged in latitude from 20°N to 53°N and in longitude from 115°W to 140°W. During this period of study the northeastern Pacific region was dominated by a semi-permanent subtropical high with north-northwesterly winds. Commercial tracks were present in practically all of the collected satellite imagery.

The Fleet Numerical Meteorology and Oceanography Center, Monterey, California (FNMOC) maintains a database of ship synoptic weather reports for both commercial and U. S. Navy units. These synoptic weather reports include ship position, course and speed and various meteorological and oceanographic parameters. Subsets of these databases for the period of study were obtained and used to identify individual tracks. After a perspective candidate for identification was located in the satellite pass, the ship's weather report was used to identify the ship associated with the track. To confirm the identity of a shiptrack from a weather report, the ship's reported position was extrapolated to the satellite image time using

the vessel's reported course and speed. Additionally, the ship's reported wind direction and speed were used as a second check in associating a particular track with an individual ship report.

The database of synoptic weather observations reports ship's position to the nearest tenth of a degree in latitude and longitude. Positions on a satellite image can be determined to the nearest .001 degree in latitude and longitude and navigated to the nearest hundredth of a degree. This provides for some error in associating a shiptrack with a reported ship position but this is probably within 20 km. Overall, this error should not impact identification.

III. RESULTS

A. GENERAL

The collected satellite imagery was analyzed for the presence of Navy and commercial shiptracks. Individual synoptic weather reports for Navy and commercial vessels were correlated with the appropriate satellite image.

1. Navy Unit Case Studies

A total of 306 U. S. Navy ship reports were associated with 55 satellite images. Of the 306 ship reports, the following is a break down by propulsion type: 166(54%) boiler, 23(8%) diesel, 81(26%) gas turbine and 36(12%) nuclear powered vessels.

The area of study was previously cited as the Pacific coast of the United States with collected satellite imagery extending as far west as 140° W and as far south as 20° N. This area was further broken down into two subareas, within the Catalina Island region and outside this region. The bulk of the ship reports from the FNMOC database were in the Catalina Island area given the nature of local daily operations of Navy units. Of the 306 total reports studied, 288 were in the Catalina Is. area. Due to the large number of ship reports in this area the probability of finding a Navy produced shiptrack should be greater. However, given the

nature of this coastal region and the nearby islands along with the anthropogenic influence from coastal locations, shiptrack identification was difficult.

After the ship reports were associated with a particular satellite image, each ship position was classified as either being under stratus or clear. Additionally, each ship position, if under stratus, was examined for identifiable tracks located nearby. If the Navy ship position was under stratus, that ship report and hence that Navy unit was analyzed to have been in an environment that should be favorable to track formation. If an identifiable commercial track was located nearby, this increases the probability that the cloud is susceptible to Navy track formation. In a subjective sense "nearby" is defined to mean within the same relative cloud mass. The final classification for each ship report was whether or not it produced a track.

Of the 306 analyzed ship reports and associated satellite imagery, 3 Navy shiptracks were correlated with their reported positions. These three identified Navy units have the following propulsion types: 2 boilers, 1 diesel. In the following individual case studies the boilers will be designated USS1 and USS2, and the diesel case study will be USS3. These designations are used to keep these results unclassified.

A total of 166 reports from boiler type propulsion units were associated with satellite imagery in the two areas

of study. Of these 166 reports, 113 were under cloud and 53 were under no cloud. The 113 under cloud reports were further subdivided into 93 reports with no identifiable tracks and 20 with tracks. Therefore, of the 20 possibilities favorable to Navy shiptrack formation, 2 were observed.

A total of 23 reports from diesel type propulsion units were analyzed, 15 reports were under cloud and 8 were under no cloud. The 15 reports under cloud were further subdivided into 10 reports with no identifiable tracks and 5 with tracks. Therefore, of the 5 possibilities favorable to Navy track formation, 1 was observed.

A total of 81 reports from gas turbine propulsion types analyzed were analyzed, 56 reports were under cloud and 25 were under no cloud. The 56 reports under cloud were further subdivided into 39 reports with no identifiable tracks and 17 with tracks. Therefore, of the 17 possibilities favorable to Navy track formation, 0 were observed.

A total of 36 reports from nuclear propulsion types were analyzed. Of this total, 29 were under cloud and 7 were under no cloud. These 29 reports were further broken down into 20 reports with no identifiable tracks and 9 reports with tracks. Therefore, of the 9 possibilities favorable to track formation, 0 were observed.

In considering the frequency with which the noted Navy tracks formed, the following percentages were calculated for under cloud reports:

Propulsion type 1 (boiler) - 2/113 = 0.9%

Propulsion type 2 (diesel) - 1/15 = 6.7%

Propulsion type 3 (gas turbine) - 0/56 = 0%

Propulsion type 4 (nuclear) - 0/29 = 0%

Calculated percentages under cloud with tracks:

Propulsion type 1 (boiler) - 2/20 = 10%

Propulsion type 2 (diesel) - 1/5 = 20%

Propulsion type 3 (gas turbine) - 0/17 = 0%

Propulsion type 4 (nuclear) - 0/9 = 0%

a. USS1

USS1 was previously cited as the first of two boiler type propulsion units. This unit was detected in a NOAA-12 satellite pass on 21 July 1993 at 1600Z (0900L). Figure 3 shows the shiptrack associated with USS1. The position of the track head as determined from the satellite image is 27.65°N 116.12°W. The estimated unit position as determined from the FNMOC database and extrapolated back to the image time is 27.50°N 116.10°W. The reported wind direction and speed are 350° at 29 km/hr. The calculated

relative wind direction and speed are 345° at 49 km/hr. The relative wind is defined as the wind across the bow. The direction of the shiptrack matches the relative wind direction.

b. USS2

USS2 was previously cited as the second of two boiler type propulsion units. This unit was detected in a NOAA-12 satellite pass on 21 July 1993 at 1600Z (0900L). Figure 4 shows the shiptrack associated with USS2. The position of the track head as determined from the satellite image is 27.76°N 116.18°W. The estimated unit position as determined from the FNMOC database and extrapolated back to the image time is 27.83°N 116.07°W.

In the above satellite pass the Navy shiptracks are faint curvalinear cloud lines extending southeast from the track head positions. The reported winds are out of the northwest at 320° at 31 km/hr. The calculated relative wind direction and speed are 318° at 63 km/hr.

c. USS3

USS3 was previously cited as the diesel type propulsion unit. This unit was detected in a NOAA-11 satellite pass on 23 July 1993 at 1236Z (0536L). Figure 5 shows the shiptrack associated with USS3. The position of the track head as determined from the satellite image is 32.76°N 117.58°W. The estimated unit position as determined from the FNMOC

database and extrapolated back to the image time is 37.70°N 117.52°W. The reported wind direction and speed are 300° at 18 km/hr. The calculated relative wind direction and speed are 000° at 10 km/hr.

d. Nuclear Case Study

Of the 306 total U. S. Navy reports and associated satellite imagery 36 were from nuclear powered vessels. As previously discussed, these reports were further subdivided to show that 20 were under stratus and 9 were under stratus with tracks nearby.

One of the questions posed by shiptrack researchers is whether a nuclear powered vessel can generate a track through ship wake affects. That is, if a nuclear powered vessel is transiting an area conducive to track formation, will a track form as a result of aerosols and particulate matter being mixed into the boundary layer from the surface wake affect or the ship's dynamic perturbation to the boundry layer? Figure 6 depicts an area favorable to track formation with stratus and commercial tracks nearby and no apparent track formation as a result of a transitting nuclear powered vessel.

Of the 9 unit reports that were under favorable conditions for track formation, 0 were observed. Based on these qualitative results it does not appear that nuclear

powered vessels produce shiptracks through some form of wake affect.

2. Commercial Unit Case Studies

A total of nine commercial tracks were identified and associated with a particular vessel. Satellite overviews were inspected for the presence of shiptracks as possible candidates for identification. Once a candidate track was identified, the positions of the track heads were compared to data within the synoptic weather report database obtained from FNOC. Since satellite image time and ship report time rarely match, the ship's position was determined by extrapolation from the ship report to the image time. After a quality check was performed, the track was extracted for further analysis.

a. *PGLA*

The shiptrack associated with PGLA was observed in a NOAA-12 satellite pass on 1 July 1993 at 1628Z (0928L). Figure 7 shows this shiptrack. The shiptrack head as determined from the satellite imagery is 37.04°N 131.86°W. The ship position as determined through extrapolation is 37.13°N 131.87°W. PGLA was identified as the bulk carrier OAXACA powered by oil burning engines. The shiptrack matches well with the reported meteorological conditions. The reported wind direction and speed are 010° at 33 km/hr. The calculated relative wind direction and speed are 323° at 41 km/hr.

b. WRYC

The shiptrack associated with WRYC was observed in a NOAA-12 satellite pass on 16 July 1993 at 1605Z (0905L). Figure 8 shows this shiptrack. The shiptrack head as determined from the satellite imagery is 38.41°N 129.72°W. The ship position as determined through extrapolation is 38.44°N 129.54°W. This vessel was identified as the container ship President Jackson powered by oil burning engines. The shiptrack matches well with the reported meteorological conditions. The reported wind direction and speed are 350° at 40 km/hr. The calculated relative wind direction and speed are 066° at 27 km/hr.

c. JEKN

The shiptrack associated with JEKN was observed in a NOAA-11 satellite pass on 19 August 1993 at 1209Z (0509L). Figure 9 shows this shiptrack. The shiptrack head as determined from the satellite imagery is 29.22°N 119.55°W. The ship position as determined through extrapolation is 29.17°N 119.45°W. JEKN was identified as the vehicle carrier Century Leader No. 2 powered by oil burning engines. The shiptrack matches well with the reported meteorological conditions. The reported wind direction and speed are 350° at 17 km/hr. The calculated relative wind direction and speed are 107° at 23 km/hr.

d. JKLS

The shiptrack associated with JKLS was observed in a NOAA-11 satellite pass on 17 July 1993 at 1204Z (0504L). Figure 10 shows this shiptrack. The shiptrack head as determined from the satellite imagery is 36.35°N 124.80°W. The ship position as determined through extrapolation is 36.39°N 124.78°W. JKLS was identified as the container ship Henry Hudson Bridge powered by oil burning engines. The shiptrack matches well with the reported meteorological conditions. The reported wind direction and speed are 330° at 46 km/hr. The calculated relative wind direction and speed are 050° at 13 km/hr.

e. WRYC

The shiptrack associated with this second identification of WRYC was observed in a NOAA-12 satellite pass on 17 July 1993 at 1543Z (0843L). Figure 11 shows this shiptrack. The shiptrack head as determined from the satellite imagery is 34.78°N 121.83°W. The ship position as determined through extrapolation is 34.84°N 121.85°W. The shiptrack matches well with the reported meteorological conditions. The reported wind direction and speed are 330° at 48 km/hr. The calculated relative wind direction and speed are 023° at 13 km/hr.

f. WRJP

The shiptrack associated with WRJP was observed in a NOAA-12 satellite pass on 23 July 1993 at 1654Z (0954L). Figure 12 shows this shiptrack. The shiptrack head as determined from the satellite imagery is 29.53°N 136.18°W. The ship position as determined through extrapolation is 29.61°N 136.09°W. WRJP was identified as the oil burning container vessel R. J. Pfeiffer. The shiptrack matches well with the reported meteorological conditions. The reported wind direction and speed are 060° at 37 km/hr. The calculated relative wind direction and speed are 315° at 40 km/hr.

g. DHEC

The shiptrack associated with DHEC was observed in a NOAA-12 satellite pass on 25 July 1993 at 1610Z (0910L). Figure 13 shows this shiptrack. The shiptrack head as determined from the satellite imagery is 41.15°N 132.83°W. The ship position as determined through extrapolation is 41.34°N 132.77°W. DHEC was identified as the container ship Bremen Express powered by oil burning engines. The shiptrack matches well with the reported meteorological conditions. The reported wind direction and speed are 000° at 49 km/hr. The calculated relative wind direction and speed are 035° at 58 km/hr.

h. 4XGV

The shiptrack associated with 4XGV was observed in a NOAA-12 satellite pass on 25 July 1993 at 1610Z (0910L).

Figure 14 shows this shiptrack. The shiptrack head as determined from the satellite imagery is 37.51°N 135.83°W. The ship position as determined through extrapolation is 37.52°N 135.82°W. 4XGV was identified as the container ship Zim Japan powered by oil burning engines. The shiptrack matches well with the reported meteorological conditions. The reported wind direction and speed are 020° at 18 km/hr. The calculated relative wind direction and speed are 308° at 31 km/hr.

i. WNRD

The shiptrack associated with WNRD was observed in a NOAA-12 satellite pass on 25 July 1993 at 1610Z (0910L). Figure 15 shows this shiptrack. The shiptrack head as determined from the satellite imagery is 36.55°N 126.22°W. The ship position as determined through extrapolation is 36.54°N 126.23°W. WNRD was identified as the container ship President Monroe powered by oil burning engines. The shiptrack matches well with the reported meteorological conditions. The reported wind direction and speed are 350° at 69km/hr. The calculated relative wind direction and speed are 023° at 43 km/hr.

3. Reflectance/Emittance Analysis

To further demonstrate the utility of database analysis of processed shiptrack data, an analysis of the change in reflectance/emittance between the shiptrack and the surrounding environment was performed for both the commercial and Navy shiptracks.

Figure 16 is a composite for all commercial tracks extracted from daytime satellite imagery and shows this change in reflectance as a function of time. The x-axis values of time were obtained by dividing the distance down track by the calculated relative winds. These values of time along the x-axis are then representative of the age of the shiptrack. The relative winds were vectorially determined from the reported wind speed and direction and the ship's true course and speed. As can be seen from this graph the reflectance between the ambient atmosphere and the shiptrack varies greatly as you move down track. These values range in magnitude from approximately -60%, which means that the surrounding atmosphere is much brighter than the actual shiptrack, to 90% where the track is considerably brighter than the surrounding atmosphere. A second order polynomial was fit to the data to examine this difference, a gradual increase in the reflectance difference is noted through the first 10 hours of track formation. Two possible explanations for this increase are that more CCN are forming during this early portion of the track's lifetime or there is some time lag in the cloud responding to the initial increase in CCN. Figures 17 through 23 detail the individual daytime commercial case studies for difference in reflectance as a function of time and show a general increase in reflectance in the initial stages of track formation. All but two case studies, PGLA and WRND show a

clear increase in reflectance through the first few hours of track formation.

Figures 24 and 25 are the corresponding plots for the difference in reflectance as a function of time for the Navy case studies USS1 and USS2 respectively. These graphs show a smaller difference in reflectance between the surrounding atmosphere and the actual track. These values range in magnitude from approximately -25% to 65%. These results indicate that Navy tracks are weaker and more diffuse, producing fewer aerosols and particulate matter to serve as CCN for droplet formation. Additionally, the gradual increase in the change in reflectance noted for the commercial case studies is apparent in the Navy case study USS1. The difference in reflectance increases through approximately the first hour of track formation similar to that for the commercial case studies. For the case study USS2 the reflectance difference decreases through the first 30 minutes of track life and then increases through the remainder of the shiptrack. This result is difficult to interpret but might be related to the accuracy of selecting the shiptrack head or an operational aspect of the Navy units mission.

Figures 26 and 27 display the difference in emittance between the surrounding atmosphere and the shiptrack for the commercial tracks extracted from satellite imagery during night passes. The magnitude of these values range from -25% to 10% with the bulk of the data points falling between 0% and -

5%. This indicates that the shiptrack is emitting less radiation centered at 3.7 microns than the surrounding atmosphere. This is expected given the relationship between droplet radius and emittance. Smaller droplets will emit a correspondingly lesser amount of radiation at 3.7 microns.

Figure 28 is a graph of the difference in emittance between the surrounding atmosphere and the shiptrack for the Navy track extracted from night-time satellite imagery. Although only a single Navy track was identified in night-time satellite imagery, the results are comparable to data collected for the commercial tracks with the bulk of the data points falling between 0% and -3%.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The focus of this thesis was to demonstrate the utility of database analysis of collected and processed shiptrack data. To that extent a dedicated search for Navy and commercial shiptracks was performed on satellite imagery collected during the summer months of 1993.

The results of the analysis were successful in answering some questions posed by shiptrack researchers. First, conventionally powered Navy vessels operating in environments conducive to track formation will generate shiptracks although they are weak and difficult to discern in the satellite imagery. Navy vessels do not operate under the same premise as do commercial vessels transiting the oceans. Commercial vessels are very much concerned with the economics of fuel consumption and therefore travel the most economical route between ports of call. Navy vessels transiting the oceans do so based on an operational commitment or for training purposes which may provide for transits altogether different from their commercial counterparts. Naval operations might require a Navy unit to remain within the same general area hence, not producing the characteristic long, continuous commercial shiptrack. Therefore, if a Navy vessel produces a track in an

environment susceptible to track formation, it will not necessarily appear as the distinct curvilinear feature associated with commercial tracks. Additionally, Navy conventionally powered vessels burn diesel fuel marine (DFM) in their diesels and boiler driven platforms while commercial vessels are powered by oil. The total number of Navy reports under cloud with tracks was 50, of these 50 possibilities for track formation, 3 were observed. Therefore, based on this dataset, approximately 6% of the Navy vessels operating in an environment susceptible to track formation produced a track. Of the 50 reports under cloud with tracks, 9 were from nuclear powered vessels, none of which could be associated with any track formation. Therefore, it does not appear that track formation will result from the passage of a nuclear powered vessel through an environment capable of supporting shiptrack formation.

The three identified Navy tracks were considerably less apparent in the satellite imagery than any commercial tracks. This was evidenced in the radiative signatures of these tracks. The change in reflectance and emittance between the surrounding atmosphere and the track was much less for the Navy tracks than the commercial tracks. This was expected given the type of fuel used by Navy vessels and that used by commercial vessels. The Navy vessels are much cleaner burning than the commercial vessels introducing less aerosol and particulate matter into the boundary layer.

B. RECOMMENDATIONS

This study illustrates the potential for analysis of shiptrack data in a database format. Considerable research remains to be completed with the large dataset available. This further research should include:

-Continued analysis of shiptracks by propulsion type. Given the large number of observed shiptracks and the capability of identifing the propulsion type associated with the individual tracks, an analysis by propulsion type could yield valuable information on the characteristics of diesel, oil and steam generated shiptracks.

-Comparison of the radiative signatures between propulsion types. Specifically, are shiptracks generated by oil driven propulsion systems more reflective than those generated by diesel driven systems? Are the emittance values significantly different between propulsion types?

-A continuing search for Navy produced tracks. Navy shiptracks are weak and diffuse and difficult to discern in satellite imagery. Continued identification of Navy produced tracks might lead to an understanding of the minimum requirements for track formation.

-Analysis of the reported meteorological conditions. Database analysis of these data could lead to a better understanding of the meteorological conditions required for shiptrack formation.

-Identification and analysis of as many as possible of the 4000+ shiptracks collected during the summer of 1993. Identification and analysis of these tracks would serve as an excellent starting point for building the database.

[illegible]	[illegible]	Track ID #	[illegible]	[illegible]	[illegible]	[illegible]
37.04/131.86	n12.93182.1628	Comm1	302km	.jk file	37.13/131.87	PGLA
38.41/129.72	n12.93197.1605	Comm2	292km	.jk file	38.44/129.54	WRYC
29.22/119.55	n11.93231.1209	Comm3	318km	.jk file	29.17/119.45	JEKN
36.35/124.80	n12.93198.1204	Comm4	196km	.jk file	36.38/124.79	JKLS
34.78/121.83	n12.93198.1543	Comm5	384km	.jk file	34.84/121.85	WRYC
29.53/136.19	n12.93204.1654	Comm6	281km	.jk file	29.61/136.09	WRJP
41.15/132.83	n12.93206.1610	Comm7	128km	.jk file	41.33/132.77	DHEC
37.51/135.83	n12.93206.1610	Comm8	165km	.jk file	37.68/135.74	[illegible]GV
36.55/126.22	n12.93206.1610	Comm9	182km	.jk file	36.67/126.14	WNRD
27.65/116.12	n12.93202.1600	USS1	98km	.jk file	27.49/116.10	NNUL
27.76/116.18	n12.93202.1600	USS2	67km	.jk file	27.83/116.07	NHBJ
32.76/117.59	n11.93204.1236	USS3	51km	.jk file	32.70/117.52	NHTB

Ship Name	Ship Length	Ship Speed	Propulsion Type/Engine HP	[illegible]	[illegible]	[illegible]		[illegible]
Jaxaca	195m	18kts	Oil		B. carrier			
Pres. Jackson	275m	24.3kts	Oil		Container			
Cent. Lor no.2	184m	18kts	Oil		V. carrier			
H. Hudson Bnc.	241m	22.5kts	Oil		Container			
Pres. Jackson	275m	24.3kts	Oil		Container			
RJ Pfeiffer	217m	22.5kts	Oil		Container			
Bremen Exp.	287m	23kts	Oil		Container			
Zim Japan	236m	21kts	Oil		Container			
Pres. Monroe	262m	23.3kts	Oil		Container			
•			boiler					
•			boiler					
•			diesel					

Figure 2. Sample Database Fields of Analyzed Shiptracks.

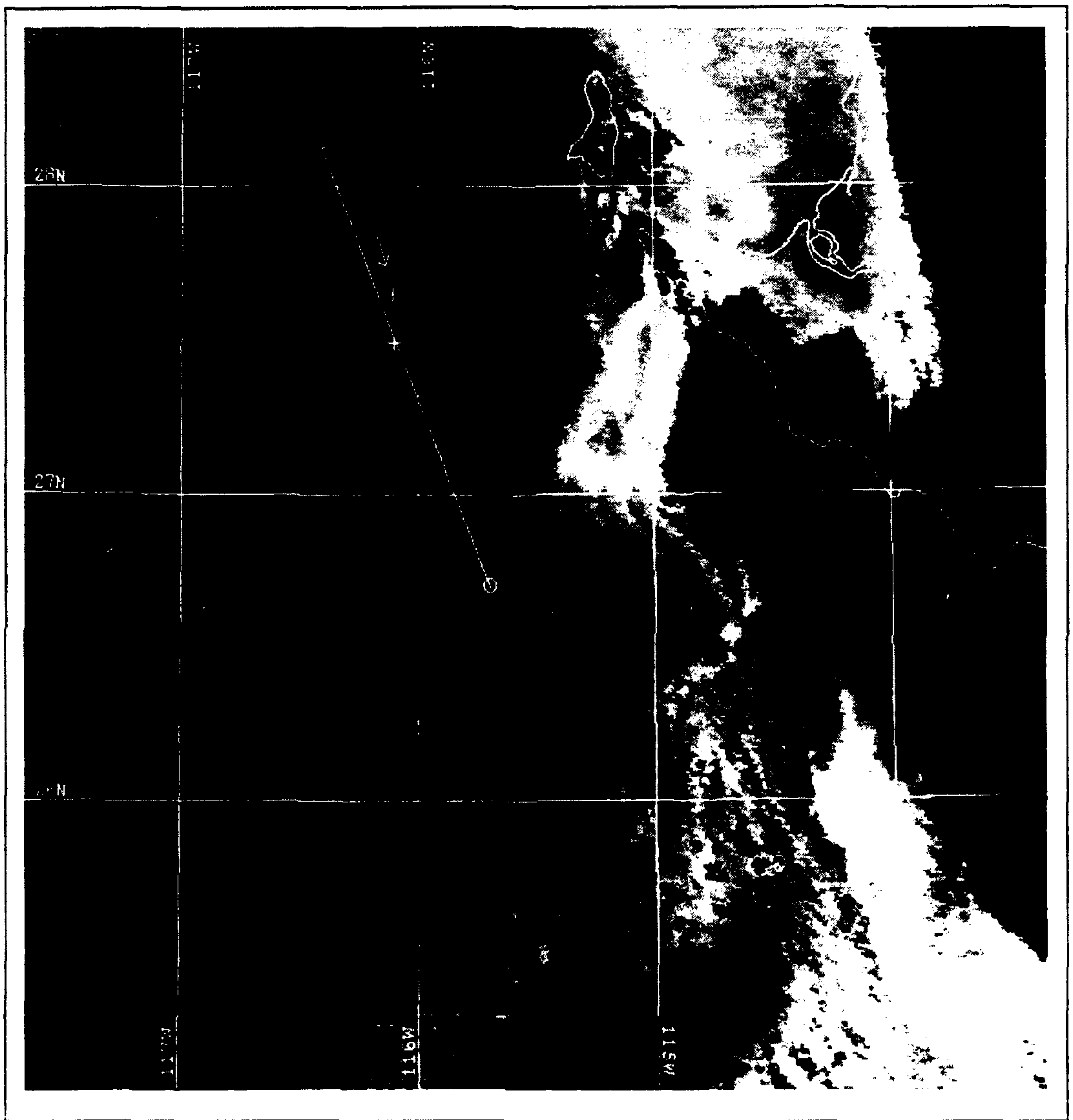

Figure 3. NOAA 12 1600Z 21 July 1993 Ch. 3 Satellite Imagery depicting USS1. Relative Wind Direction 345°.

Figure 4. NOAA 12 1600Z 21 July 1993 Ch. 3 Satellite Imagery depicting USS2. Relative Wind Direction 318°.

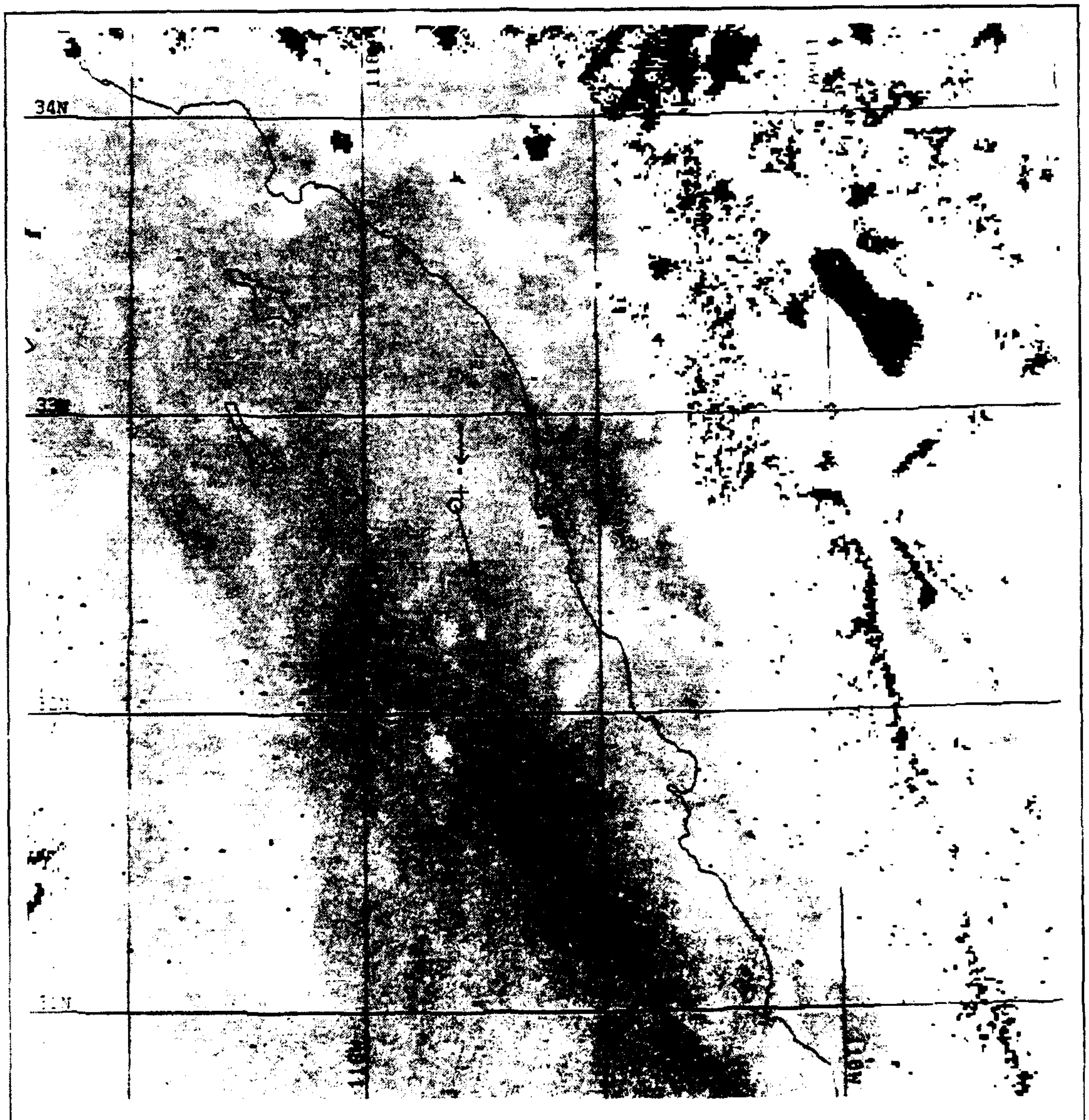

Figure 5. NOAA 11 1236Z 23 July 1993 Ch. 3 Satellite Imagery depicting USS3. Relative Wind Direction 000°.

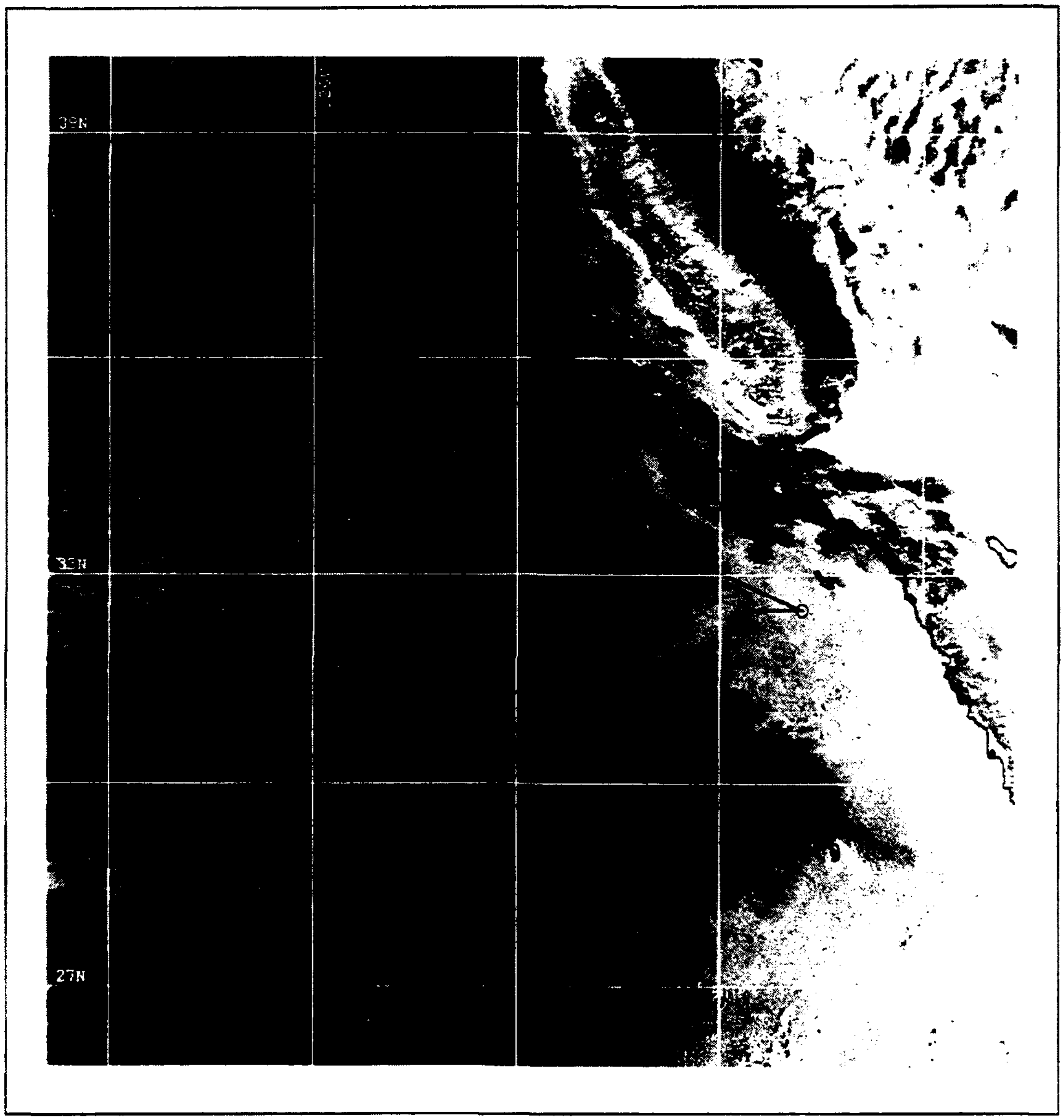

Figure 6. NOAA 12 1605Z 30 July 1993 Ch. 3 Satellite Imagery Showing Favorable Conditions for Track Formation. Plotted Positions are the Approximate Locations of a Nuclear Powered Vessel.

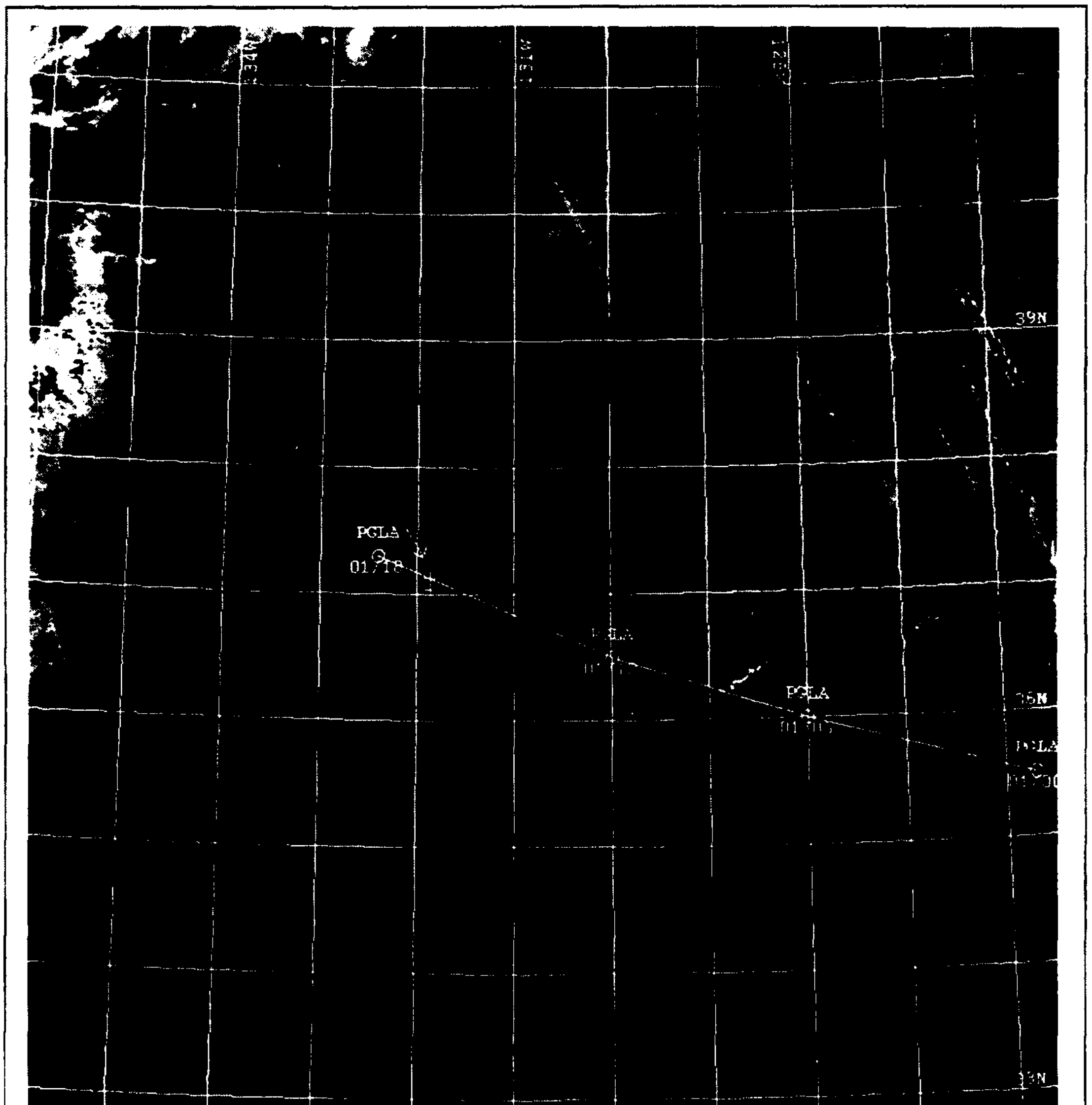

Figure 7. NOAA 12 1628Z 1 July 1993 Ch. 3 Satellite Imagery Depicting Bulk Carrier OAXACA (PGLA). Relative Wind Direction 323°.

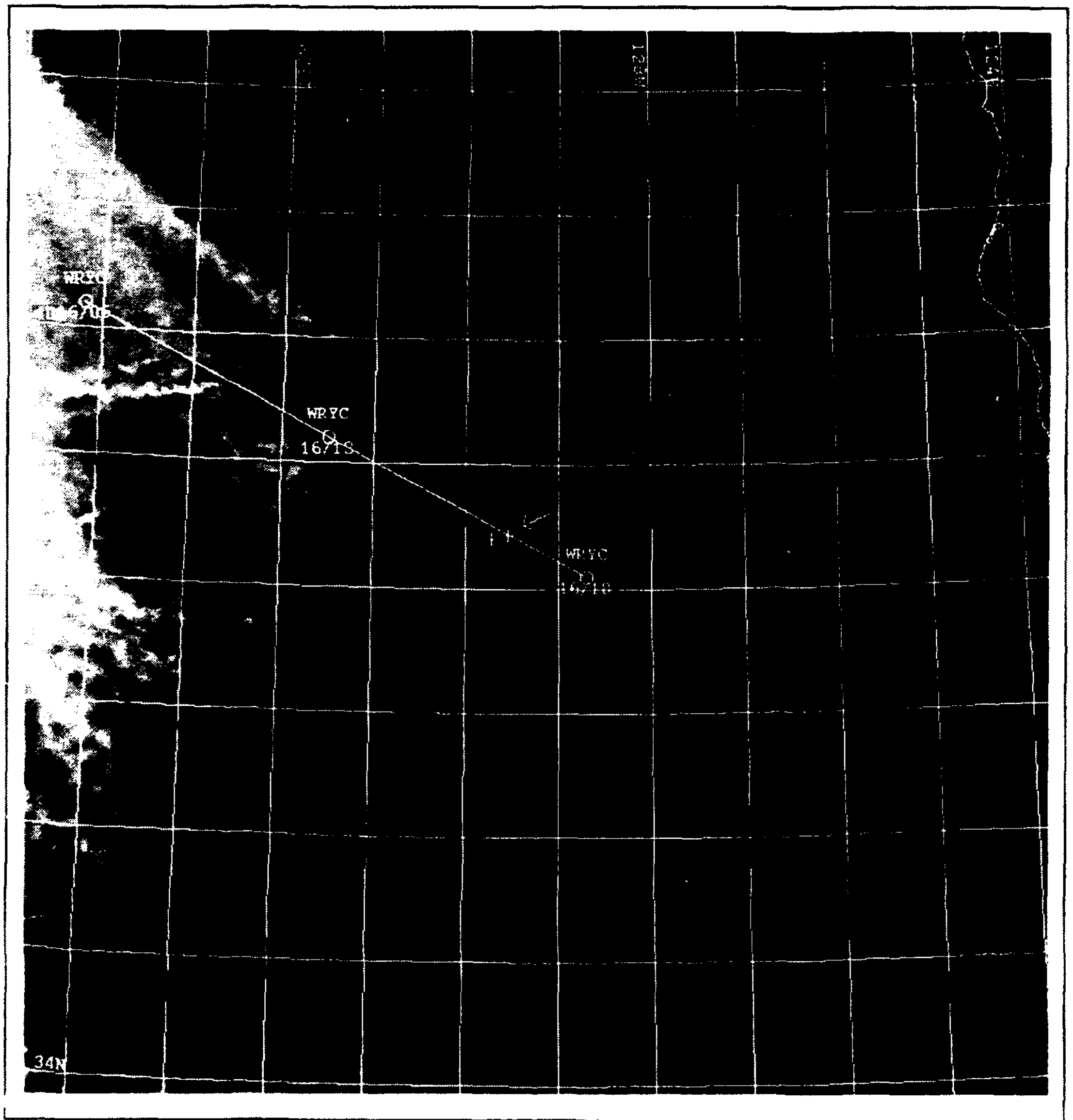

Figure 8. NOAA 12 1605Z 16 July 1993 Ch. 3 Satellite Imagery Depicting the Container Ship President Jackson (WRYC). Relative Wind Direction 066°.

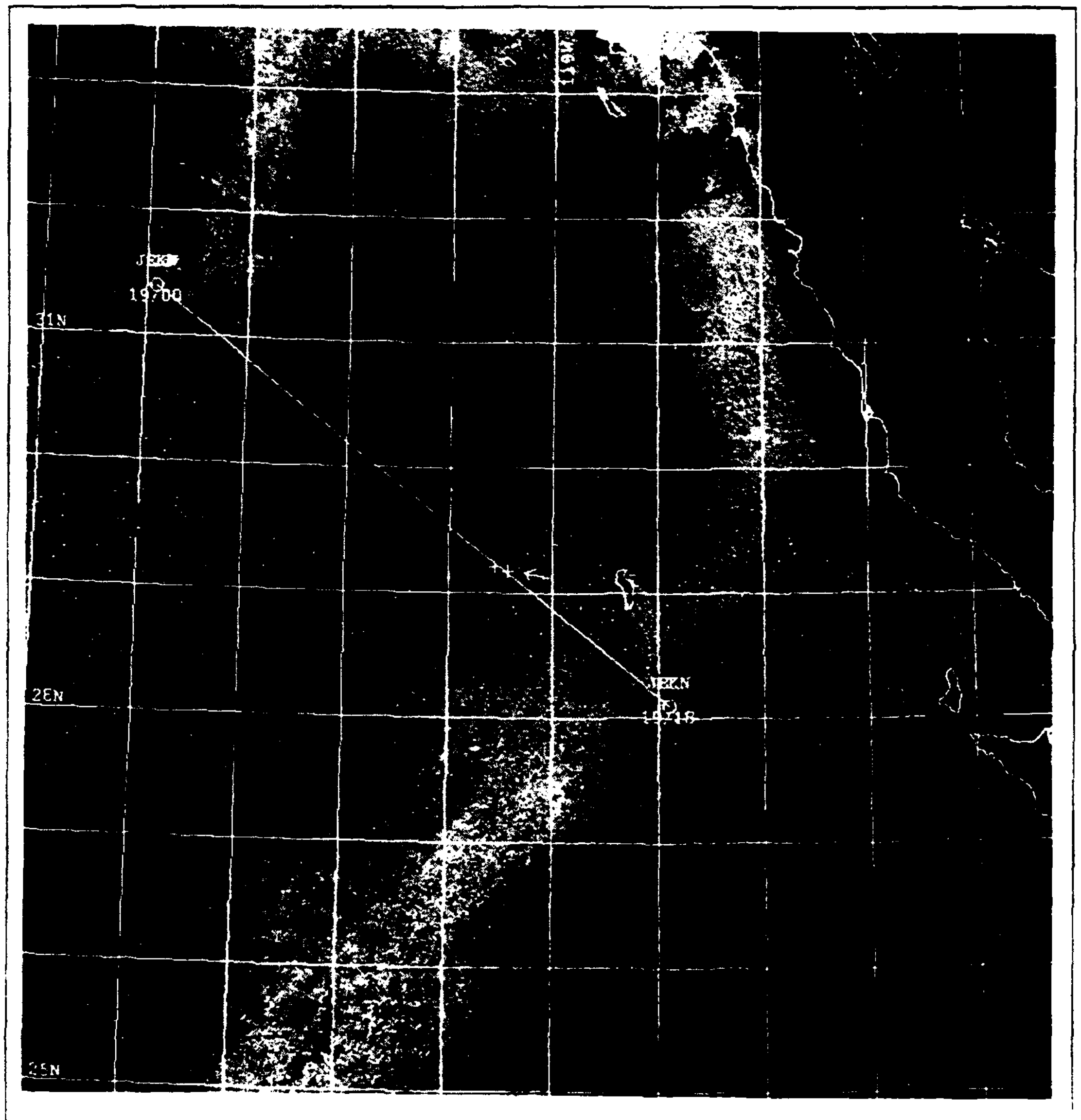

Figure 9. NOAA 11 1209Z 19 August 1993 Ch. 3 Satellite Imagery Depicting the Vehicle Carrier Century Leader No. 2 (JEKN). Relative Wind Direction 107°.

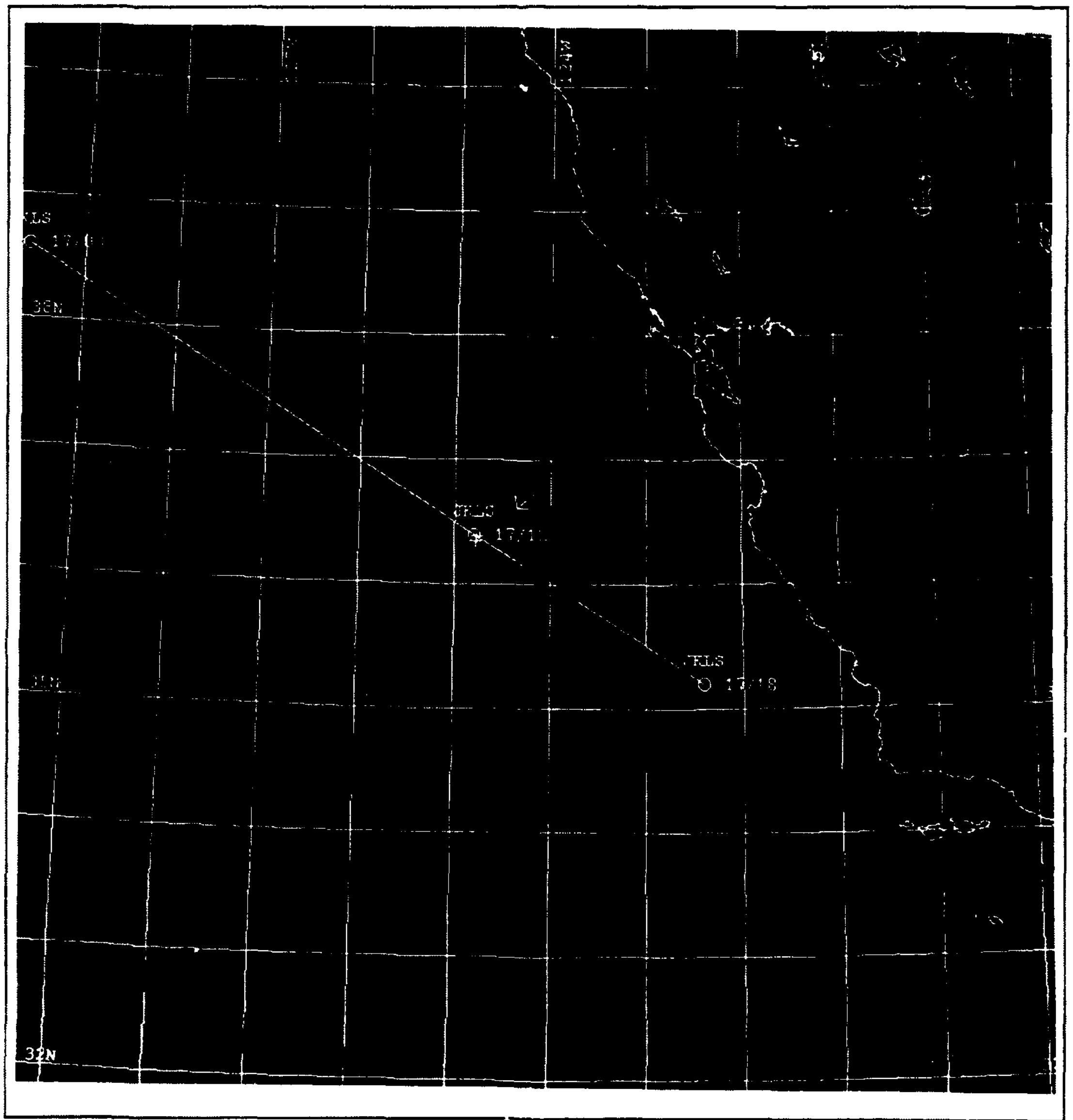

Figure 10. NOAA 11 1204Z 17 July 1993 Ch. 3 Satellite Imagery Depicting the Container Ship Henry Hudson Bridge (JKLS). Relative Wind Direction 050°.

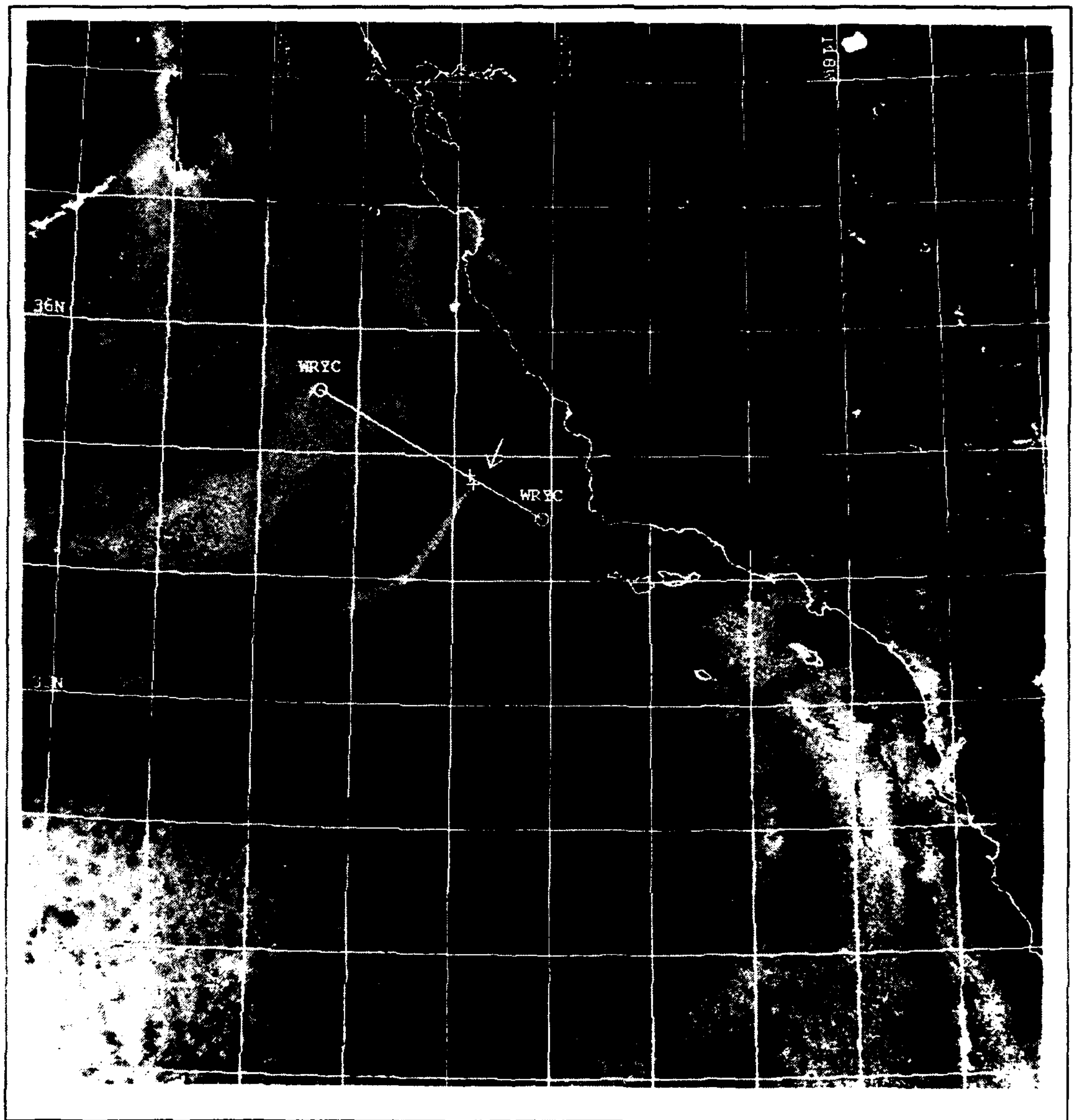

Figure 11. NOAA 12 1543Z 17 July 1993 Ch. 3 Satellite Imagery Depicting the Container Ship President Jackson (WRYC). Relative Wind Direction 023°.

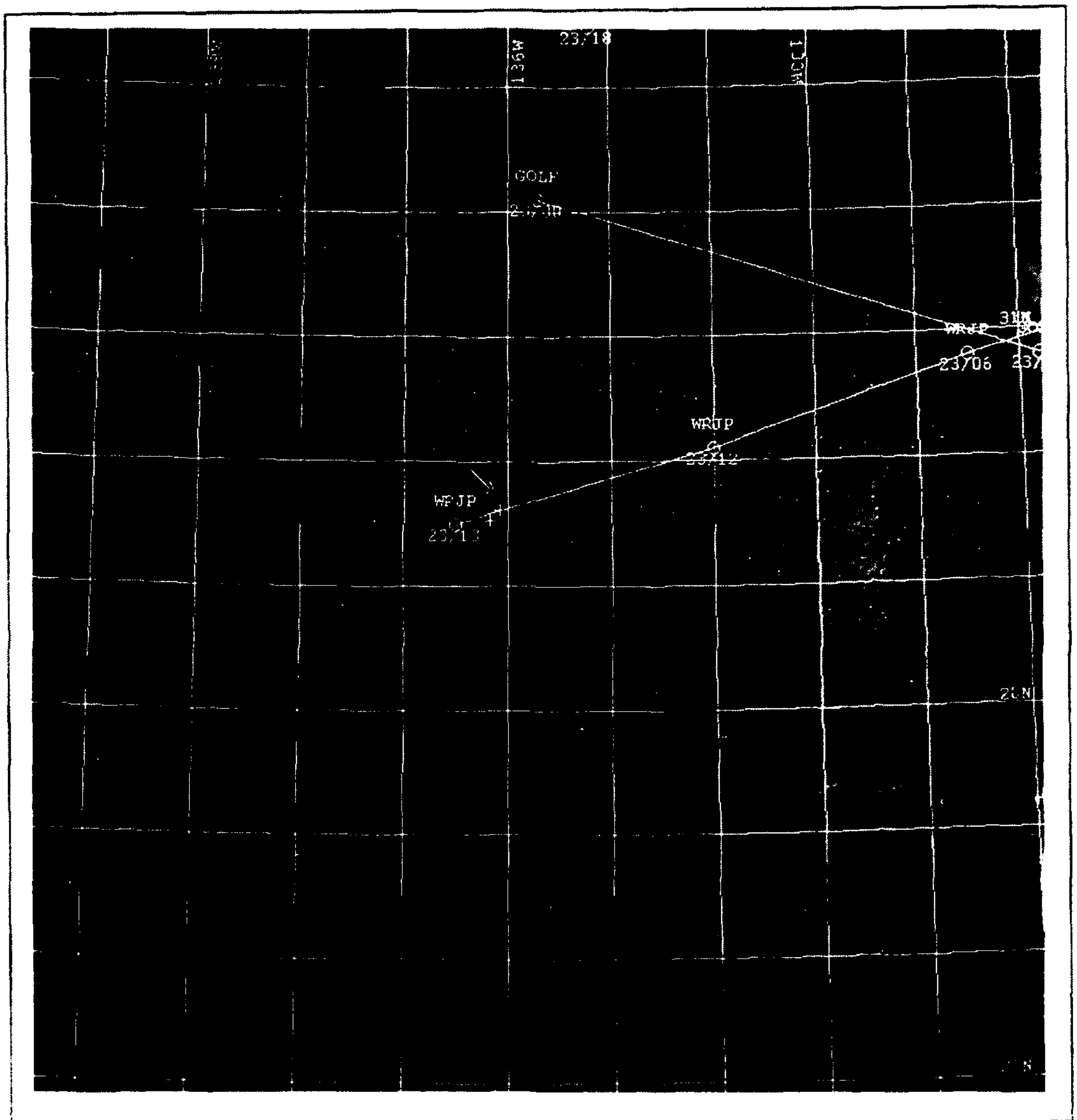

Figure 12. NOAA 12 1654Z 23 July 1993 Ch. 3 Satellite Imagery Depicting the Container Vessel R. J. Pfeiffer (WRJP). Relative Wind Direction 315°.

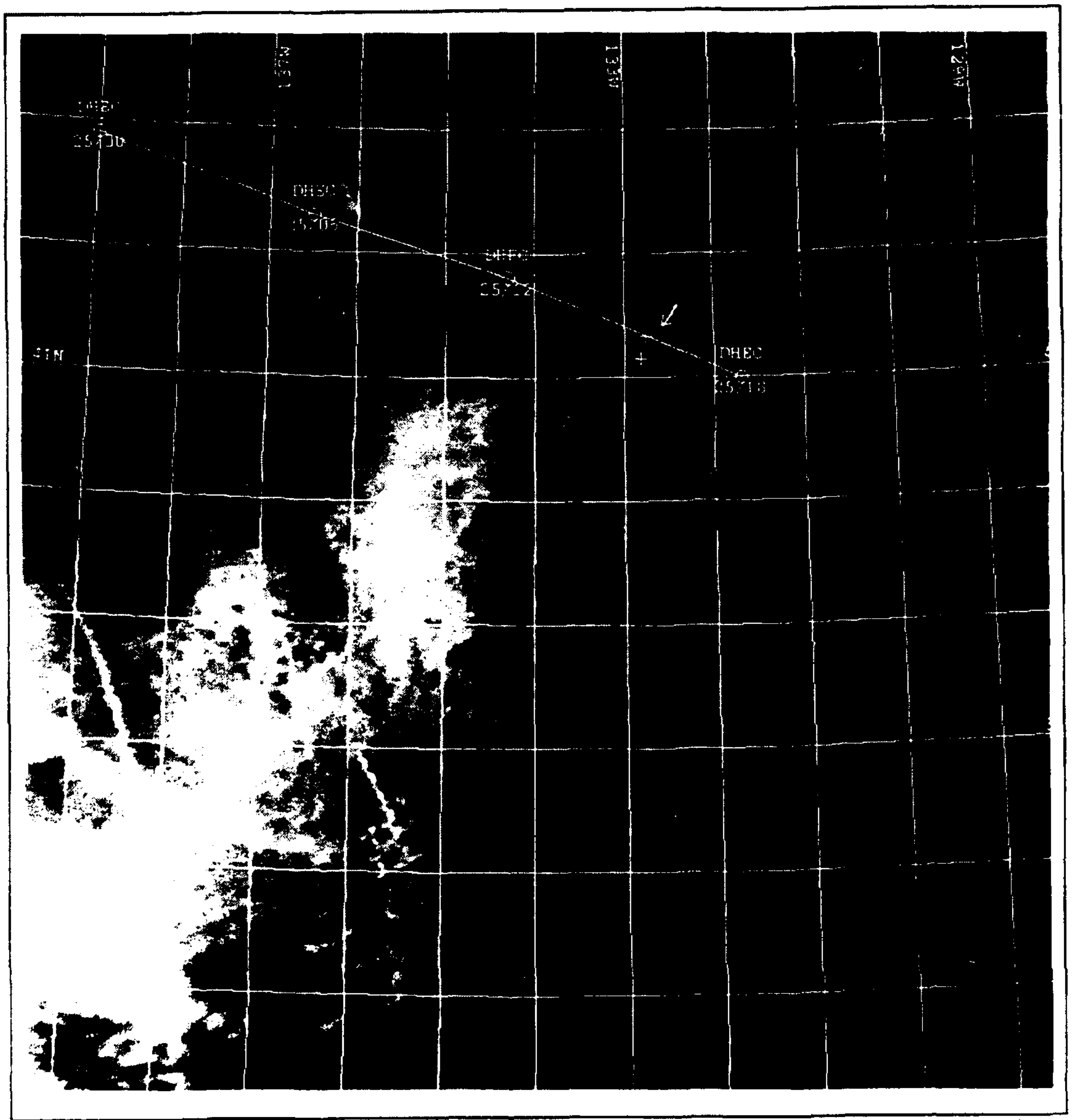

Figure 13. NOAA 12 1610Z 25 July 1993 Ch. 3 Satellite Imagery Depicting the Container Ship Bremen Express (DHEC). Relative Wind Direction 035°.

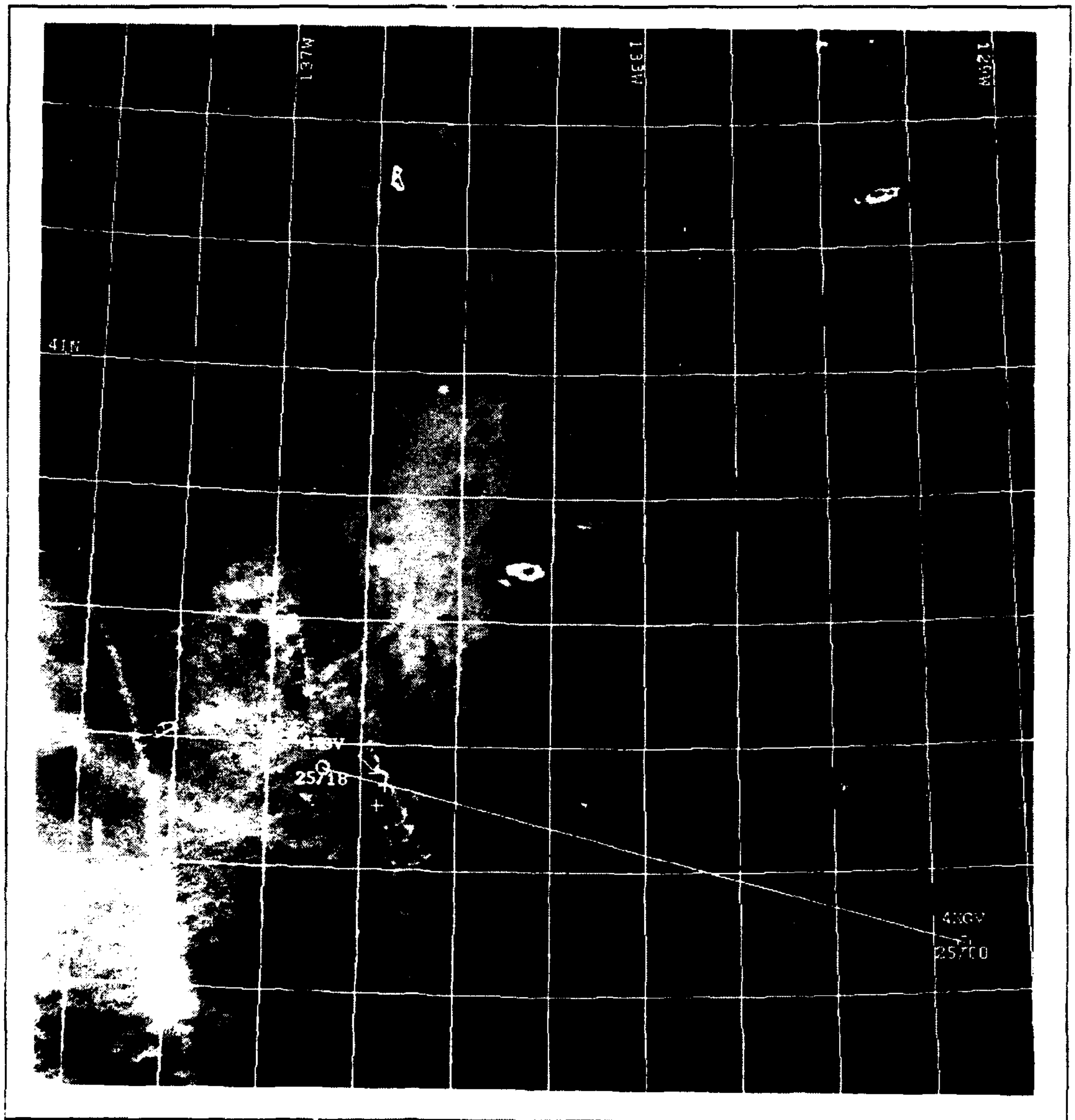

Figure 14. NOAA 12 1610Z 25 July 1993 Ch. 3 Satellite Imagery Depicting the Container Ship Zim Japan (4XGV). Relative Wind Direction 308°.

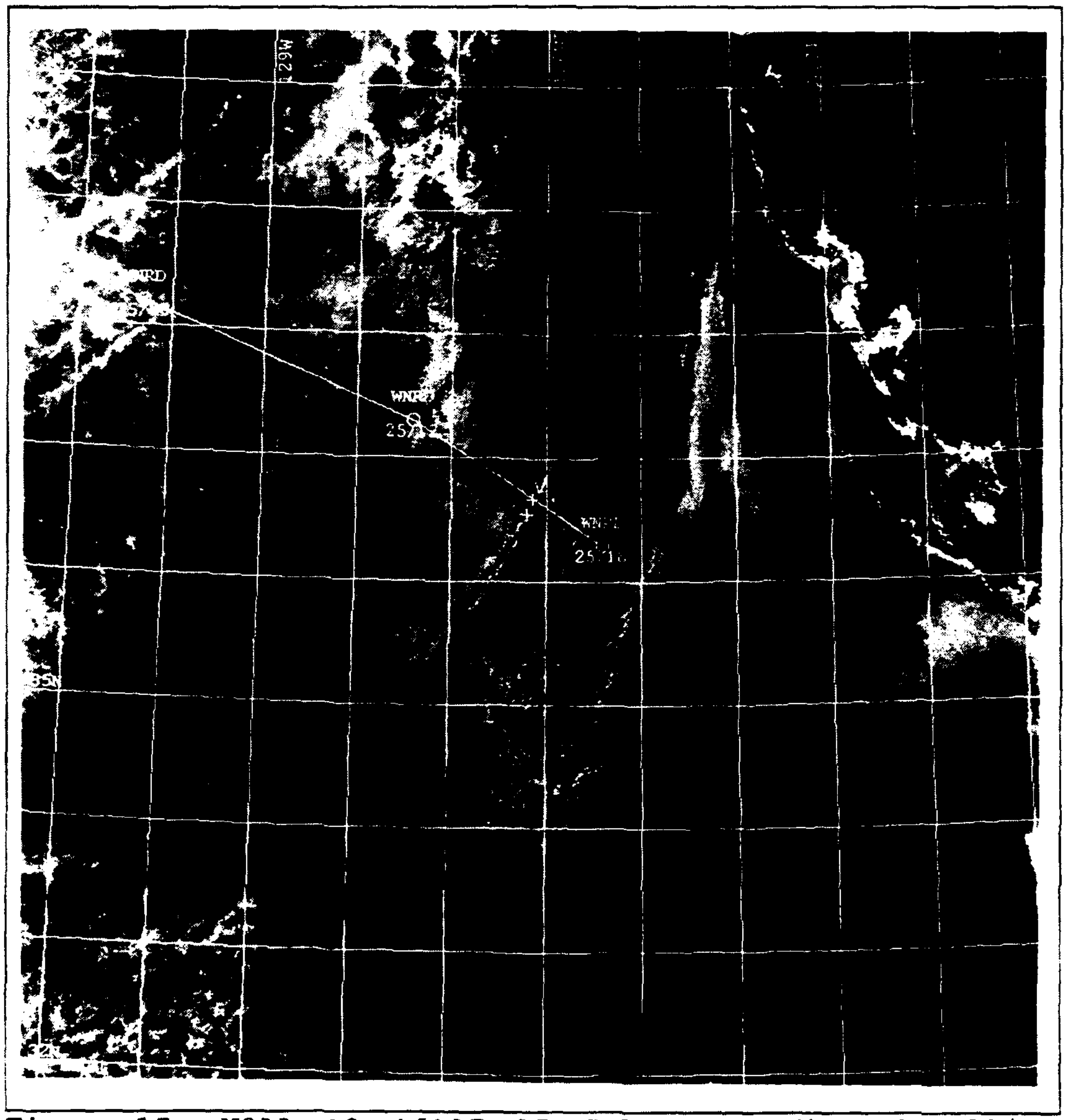

Figure 15. NOAA 12 1610Z 25 July 1993 Ch.3 Satellite Imagery Depicting the Container Ship President Monroe (WNRD). Relative Wind Direction 023°.

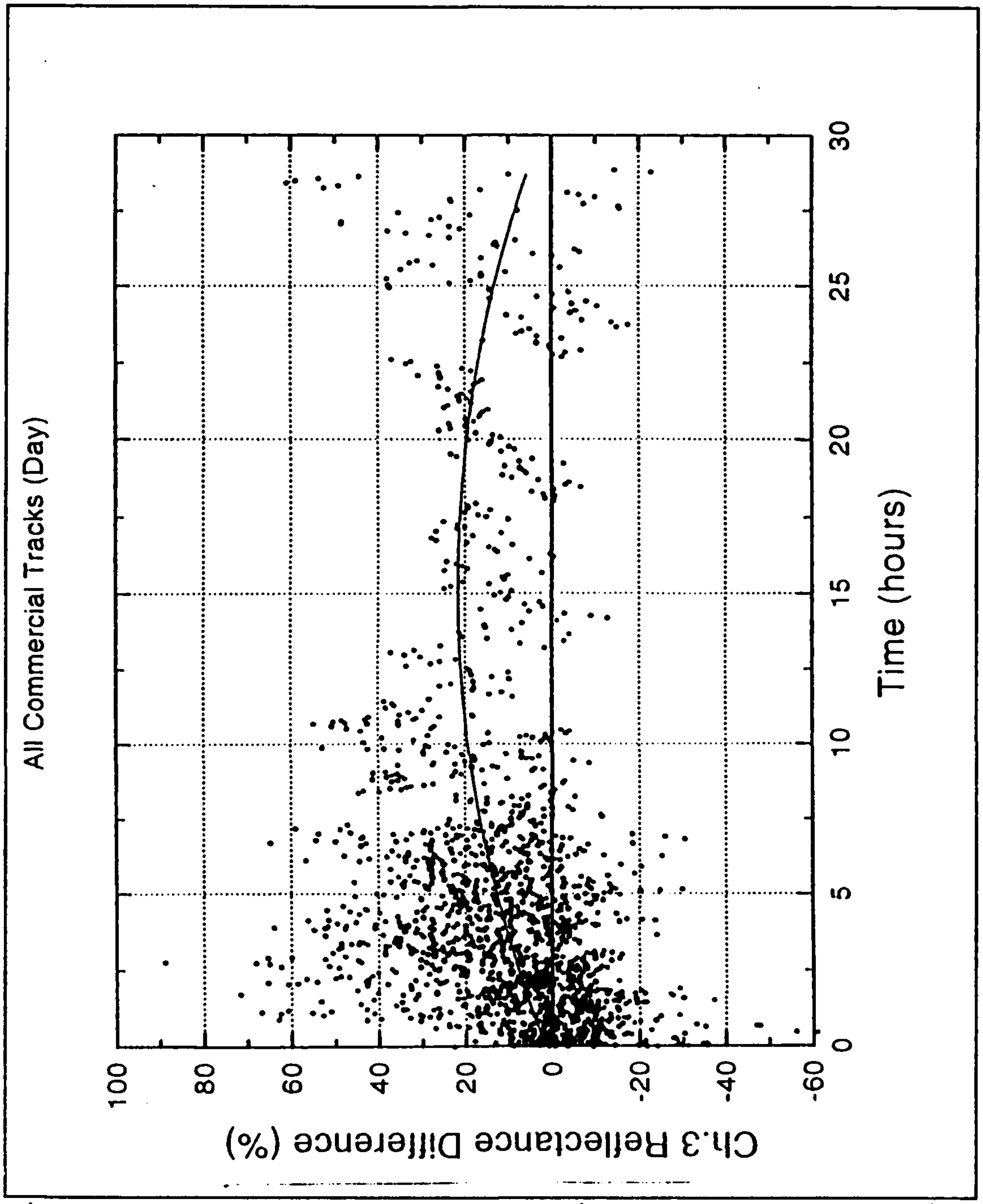

Figure 16. Chan. 3 Reflectance Difference (%) Composite for all Commercial Tracks Identified in Daytime Satellite Imagery.

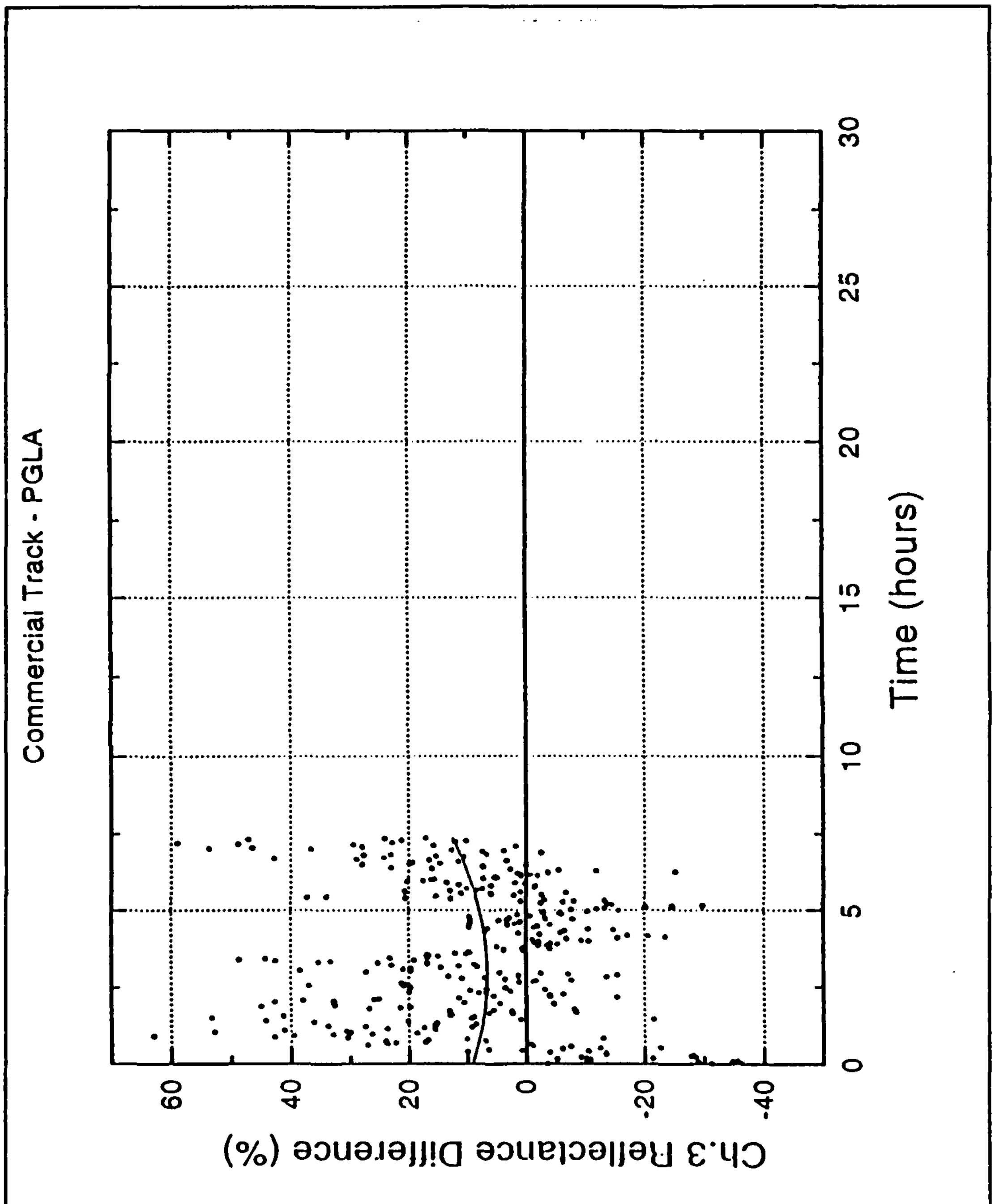

Figure 17. Chan. 3 Reflectance Difference (%) for PGLA.

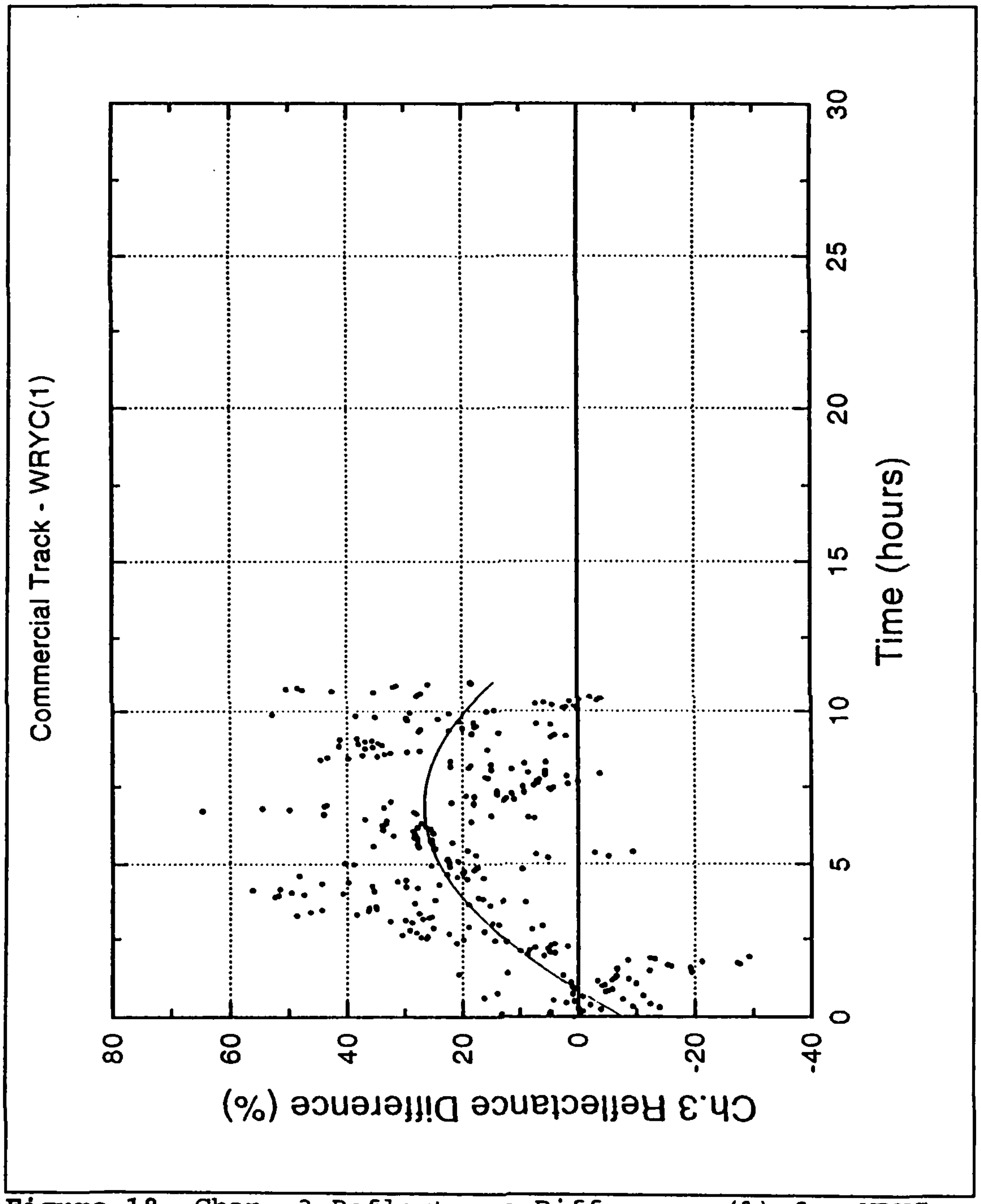

Figure 18. Chan. 3 Reflectance Difference (%) for WRYC.

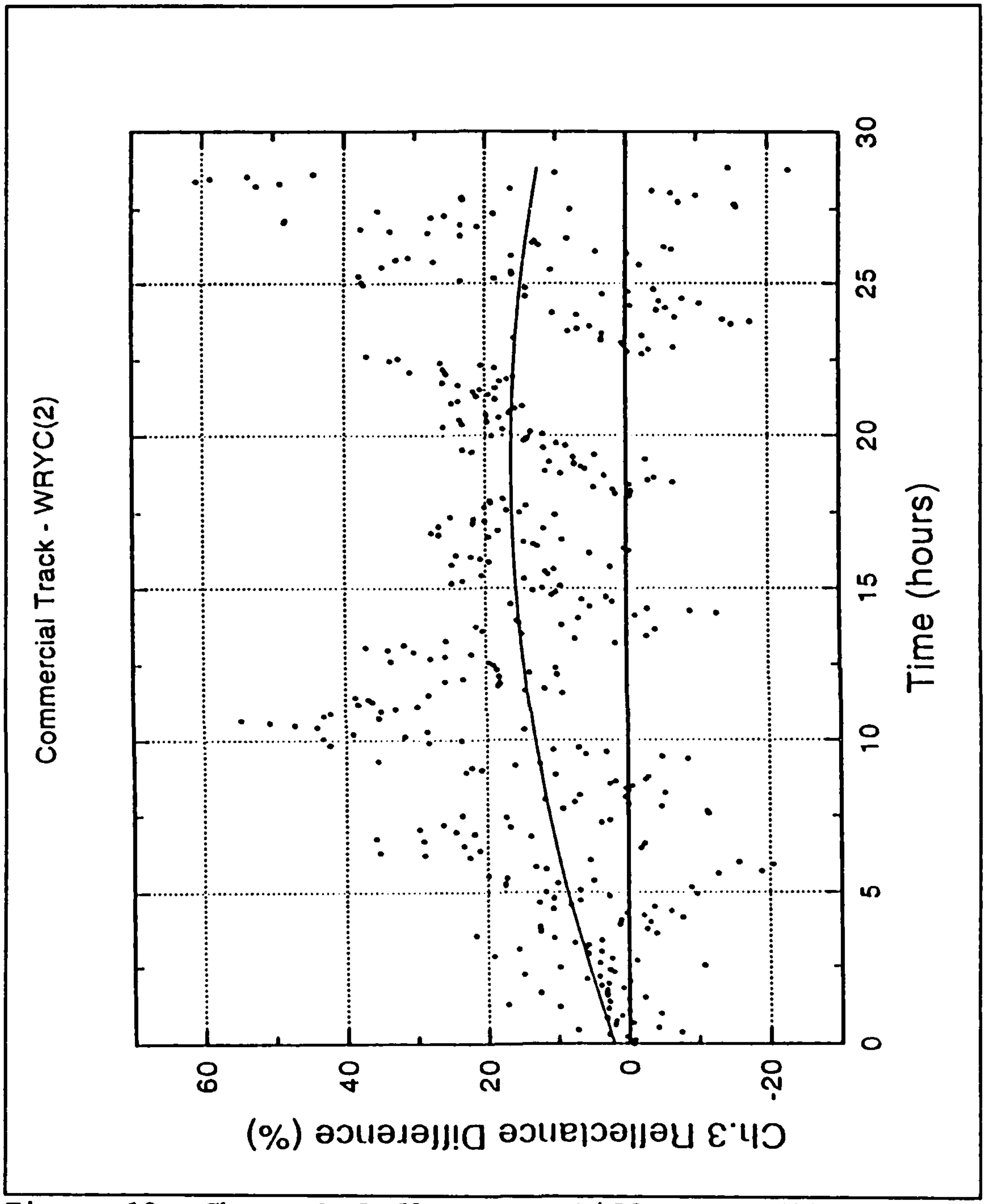

Figure 19. Chan. 3 Reflectance Difference (%) for the Second Identification of WRYC.

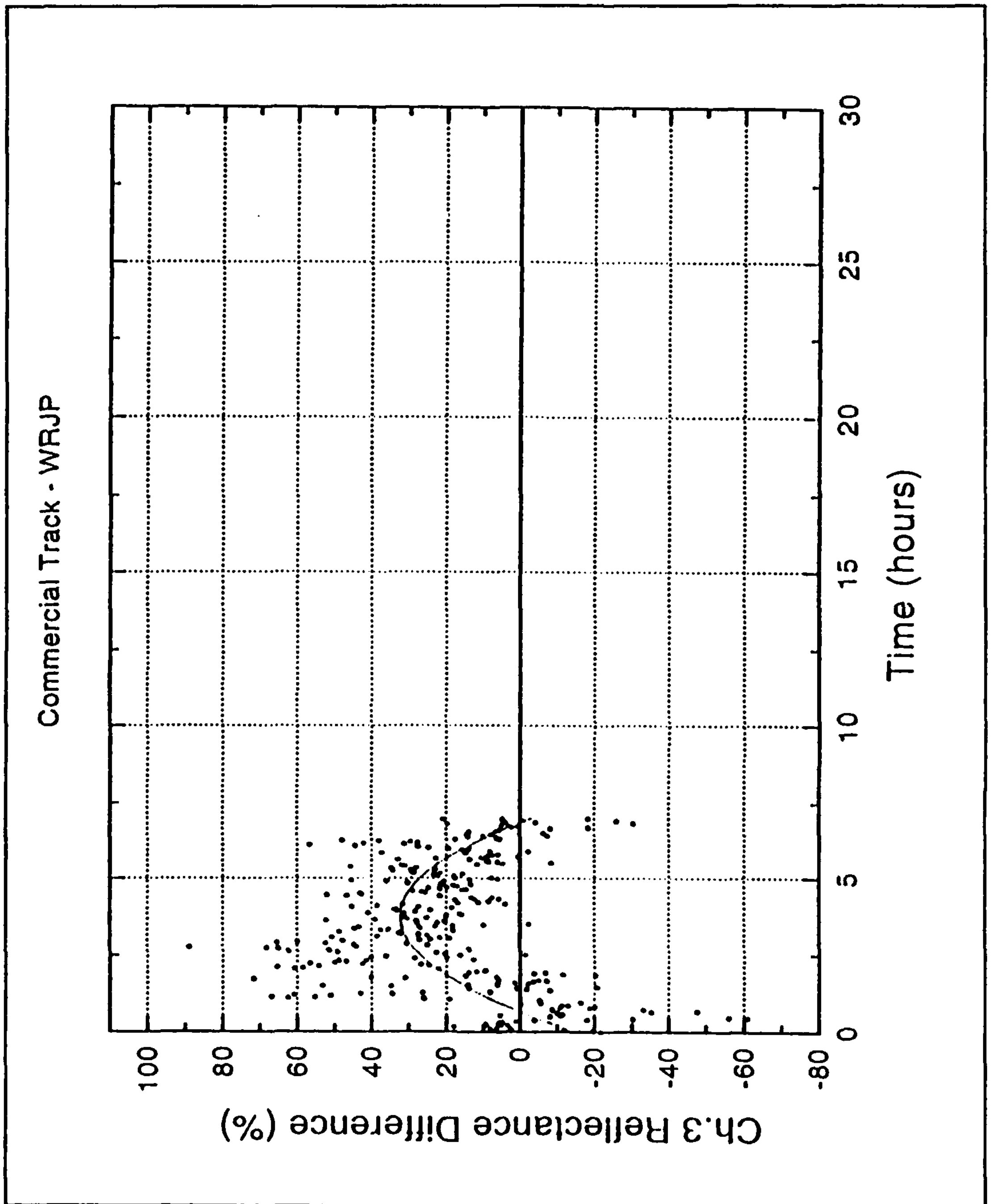

Figure 20. Chan. 3 Reflectance Difference (%) for WRJP.

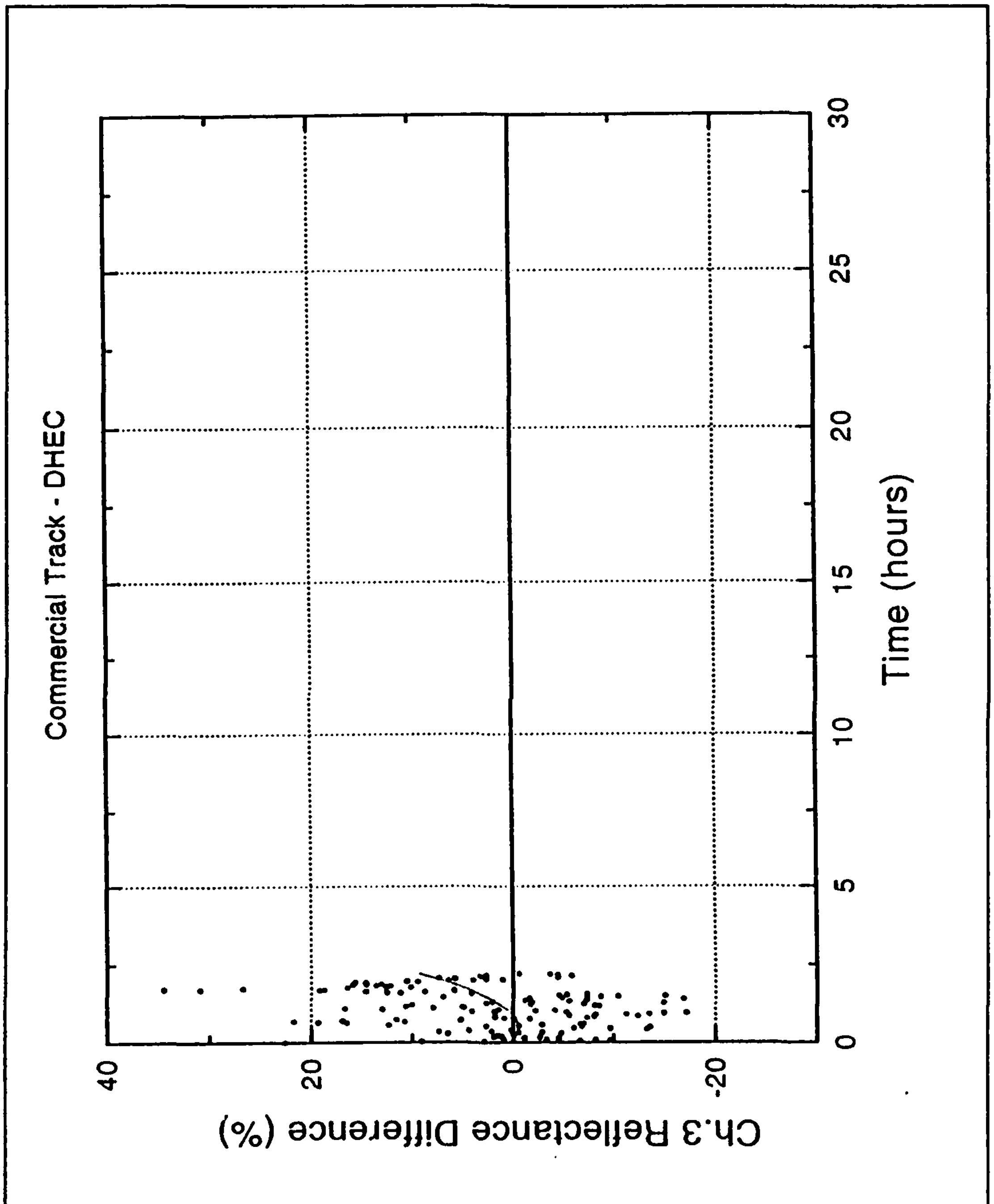

Figure 21. Chan. 3 Reflectance Difference (%) for DHEC.

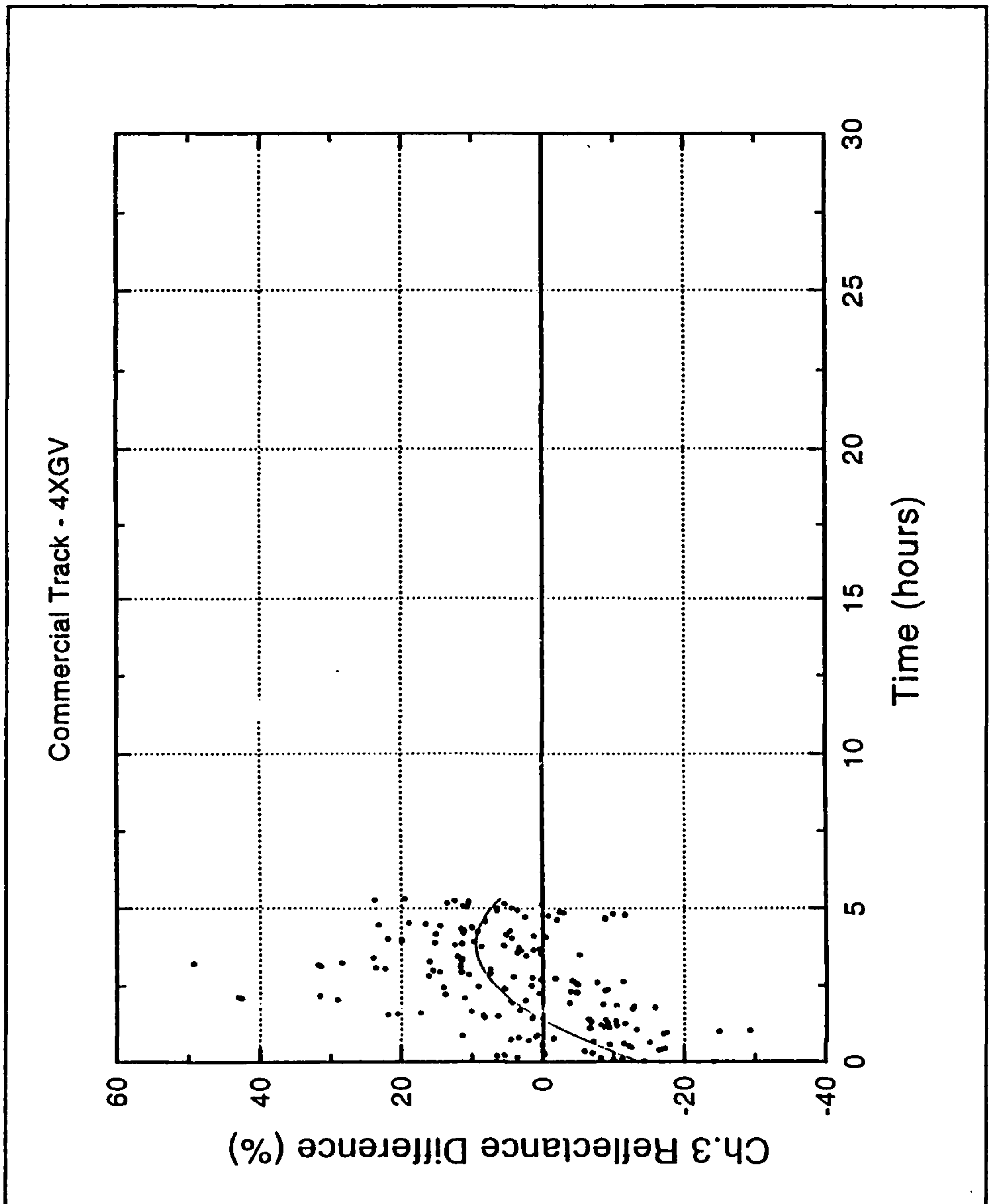

Figure 22. Chan. 3 Reflectance Difference (%) for 4XGV.

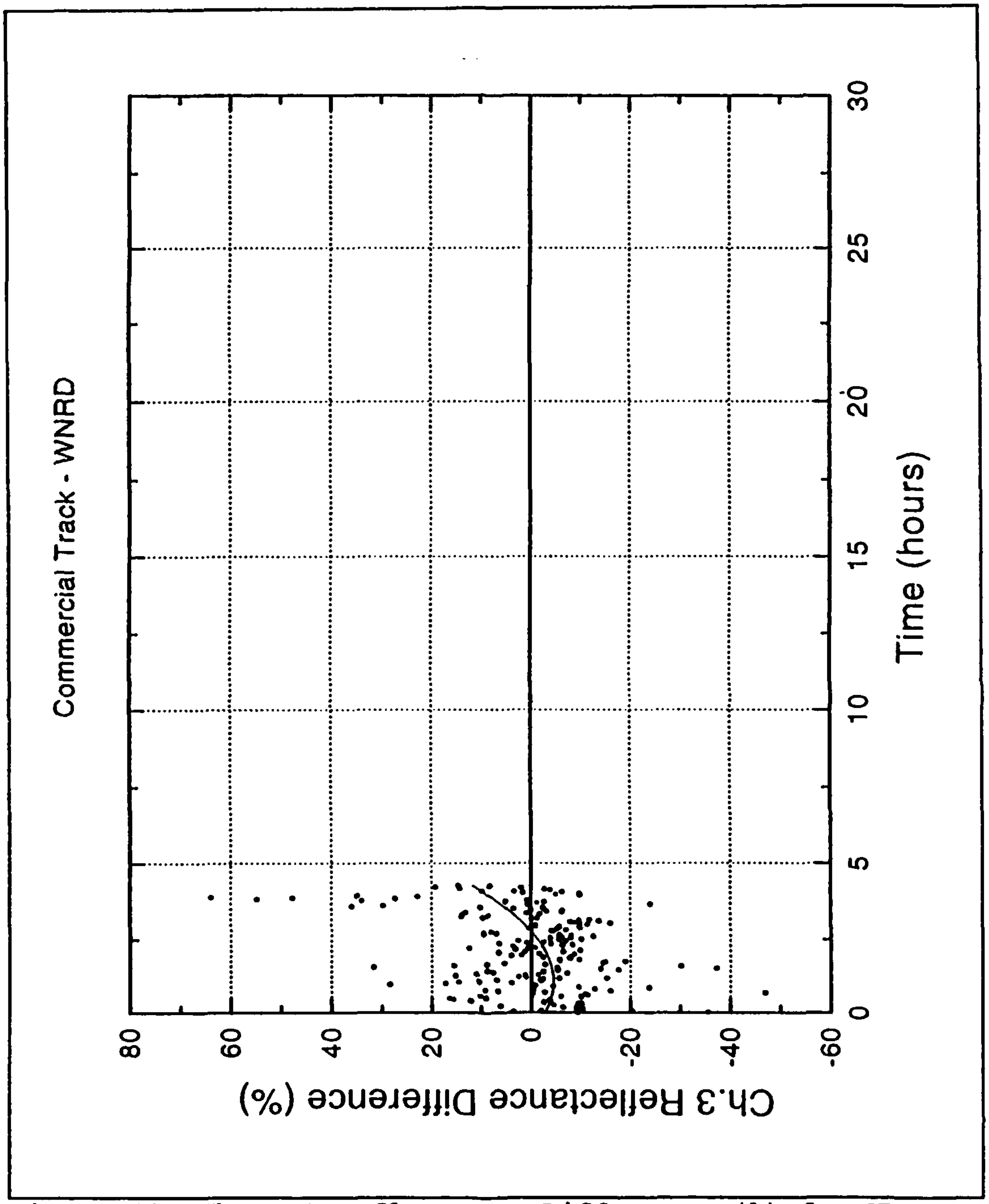

Figure 23. Chan. 3 Reflectance Difference (%) for WNRD.

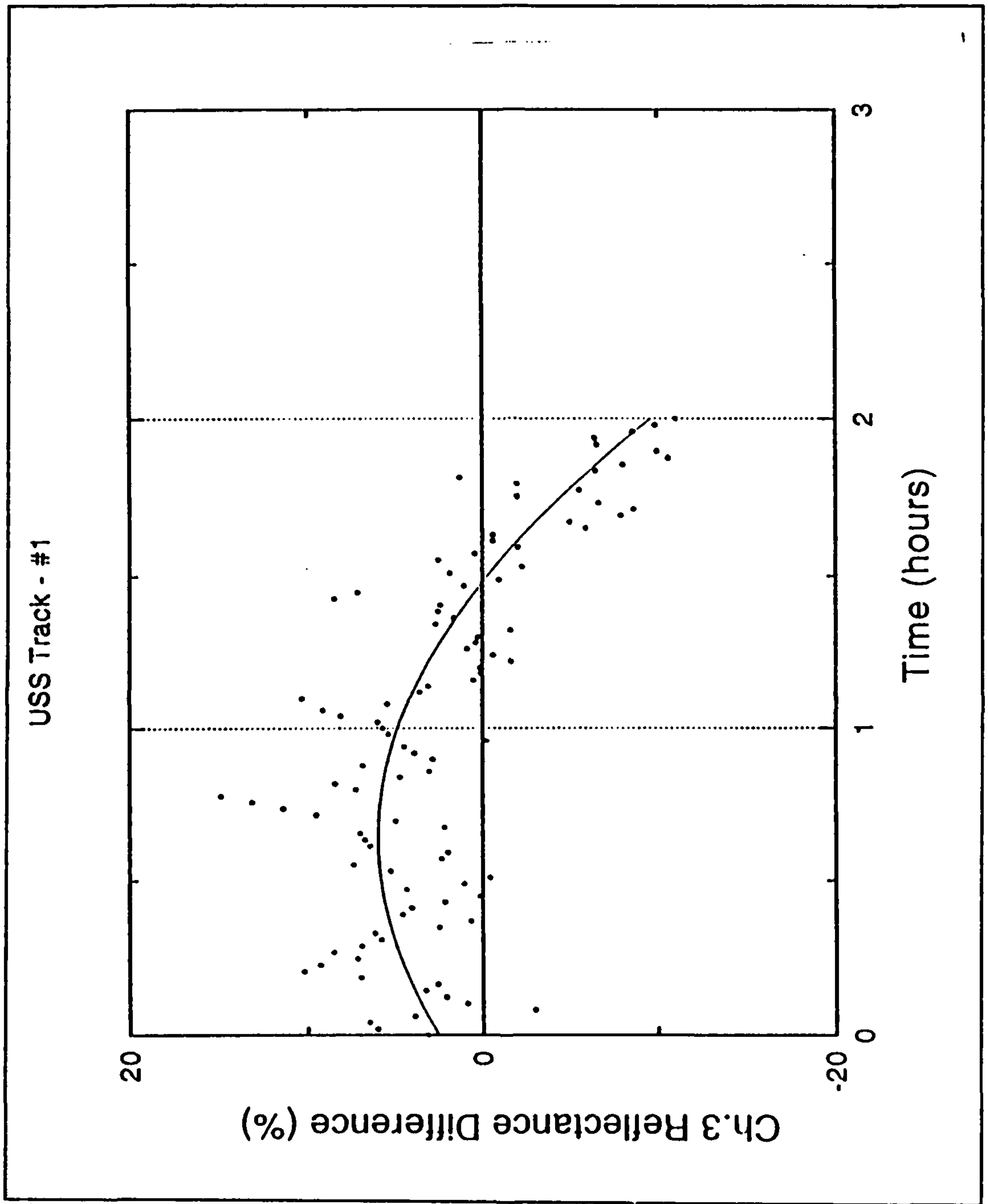

Figure 24. Chan. 3 Reflectance Difference (%) for USS1.

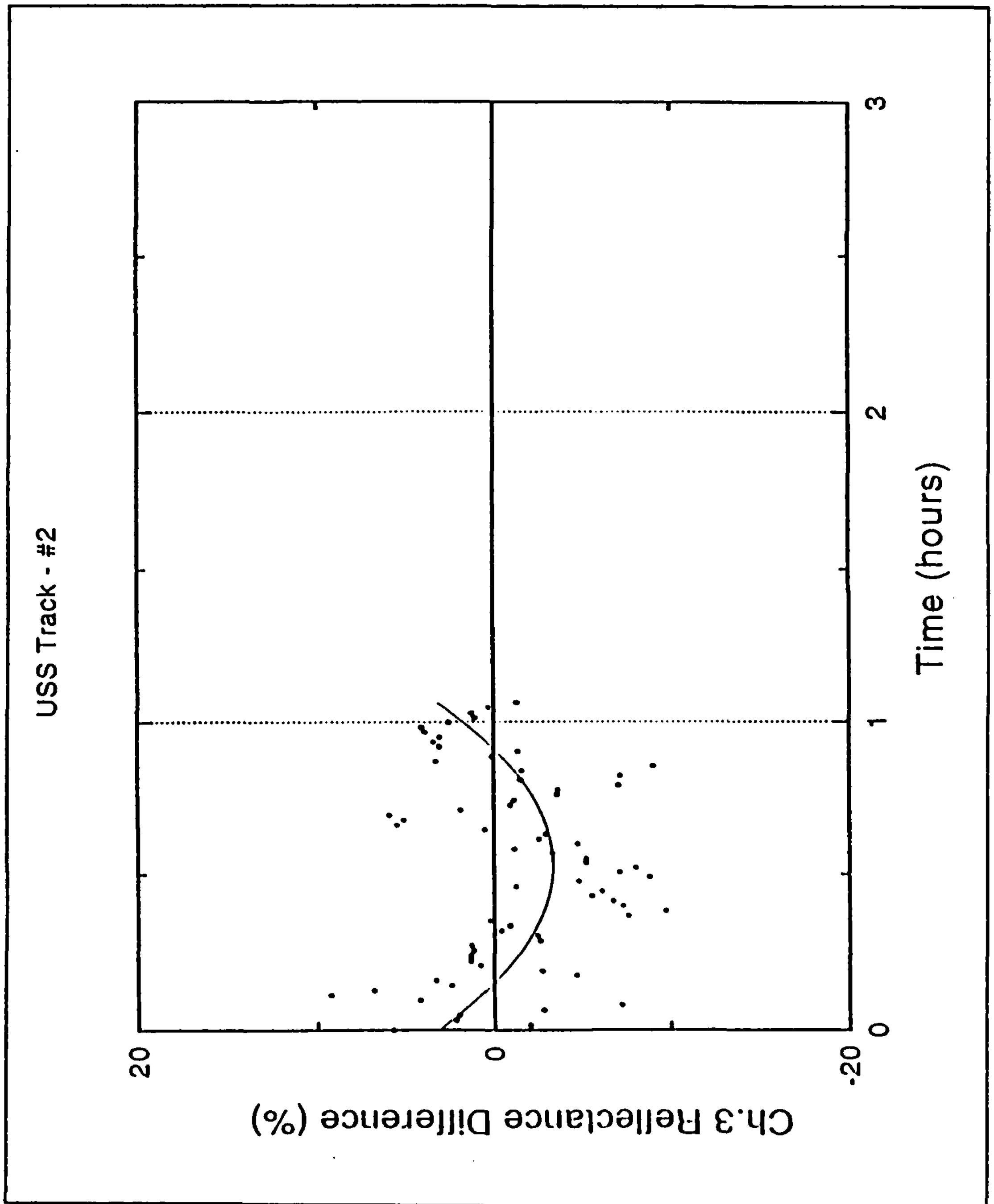

Figure 25. Chan. 3 Reflectance Difference (%) for USS2.

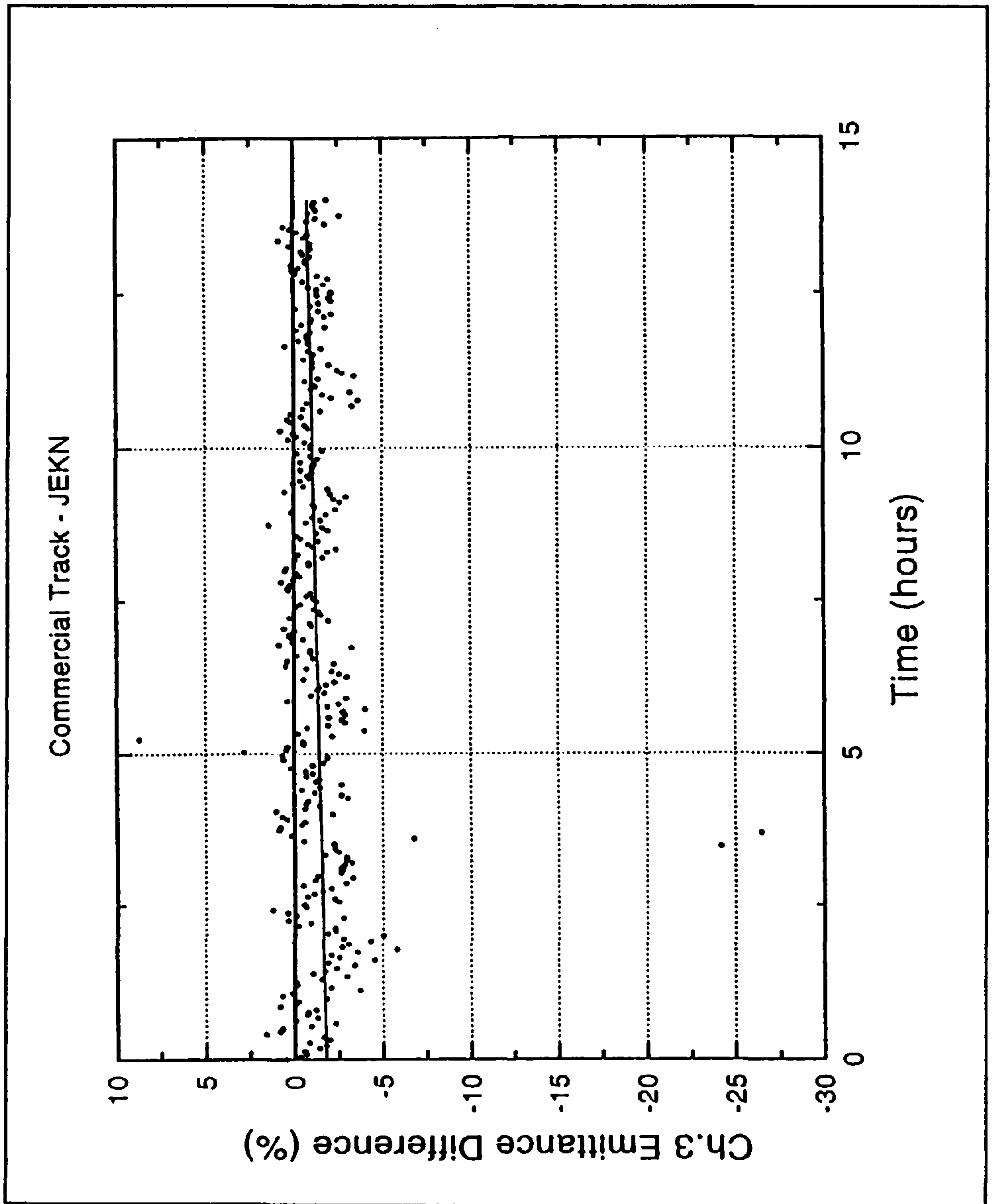

Figure 26. Chan. 3 Emittance Difference (%) for JEKN.

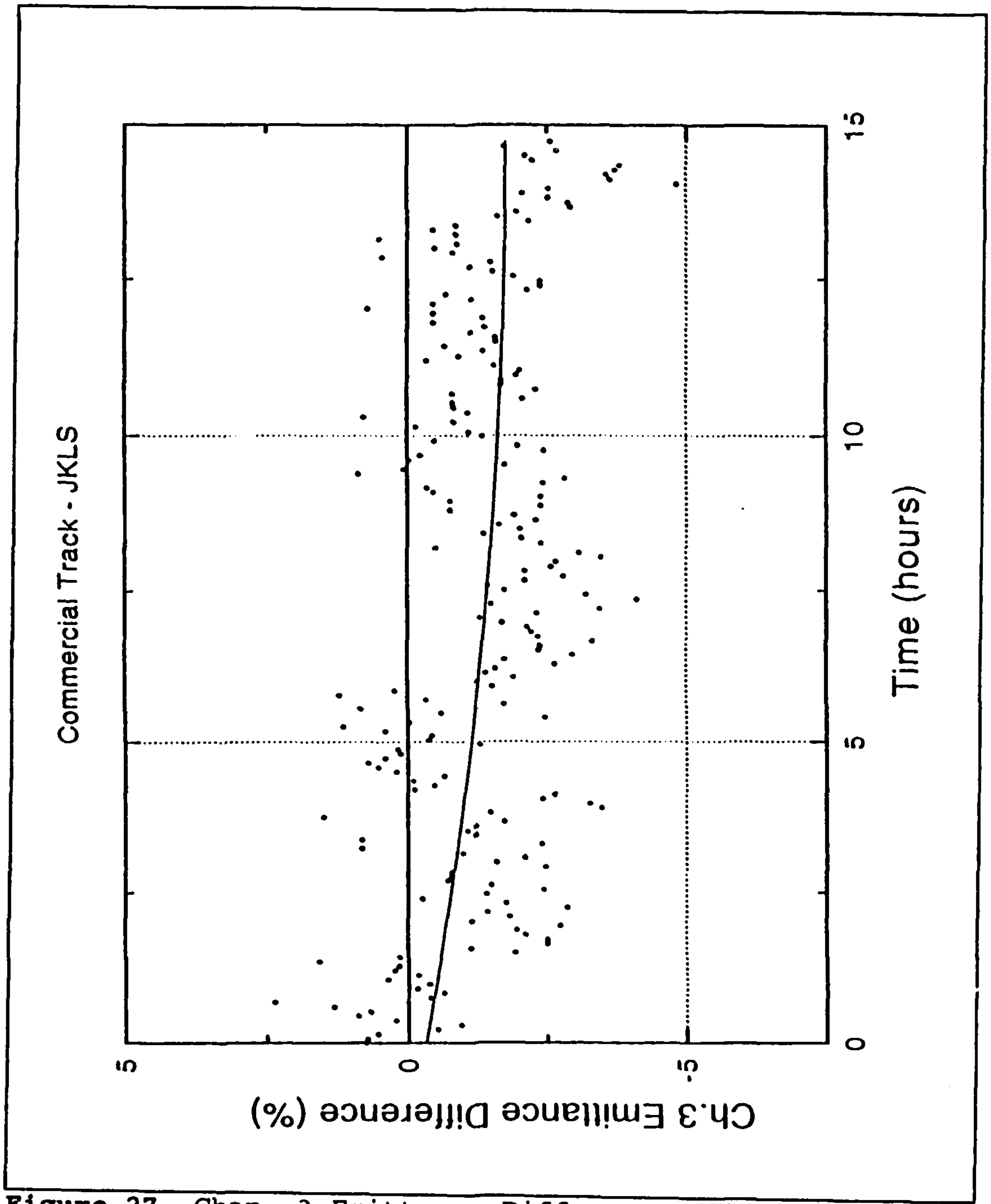

Figure 27. Chan. 3 Emittance Difference (%) for JKLS.

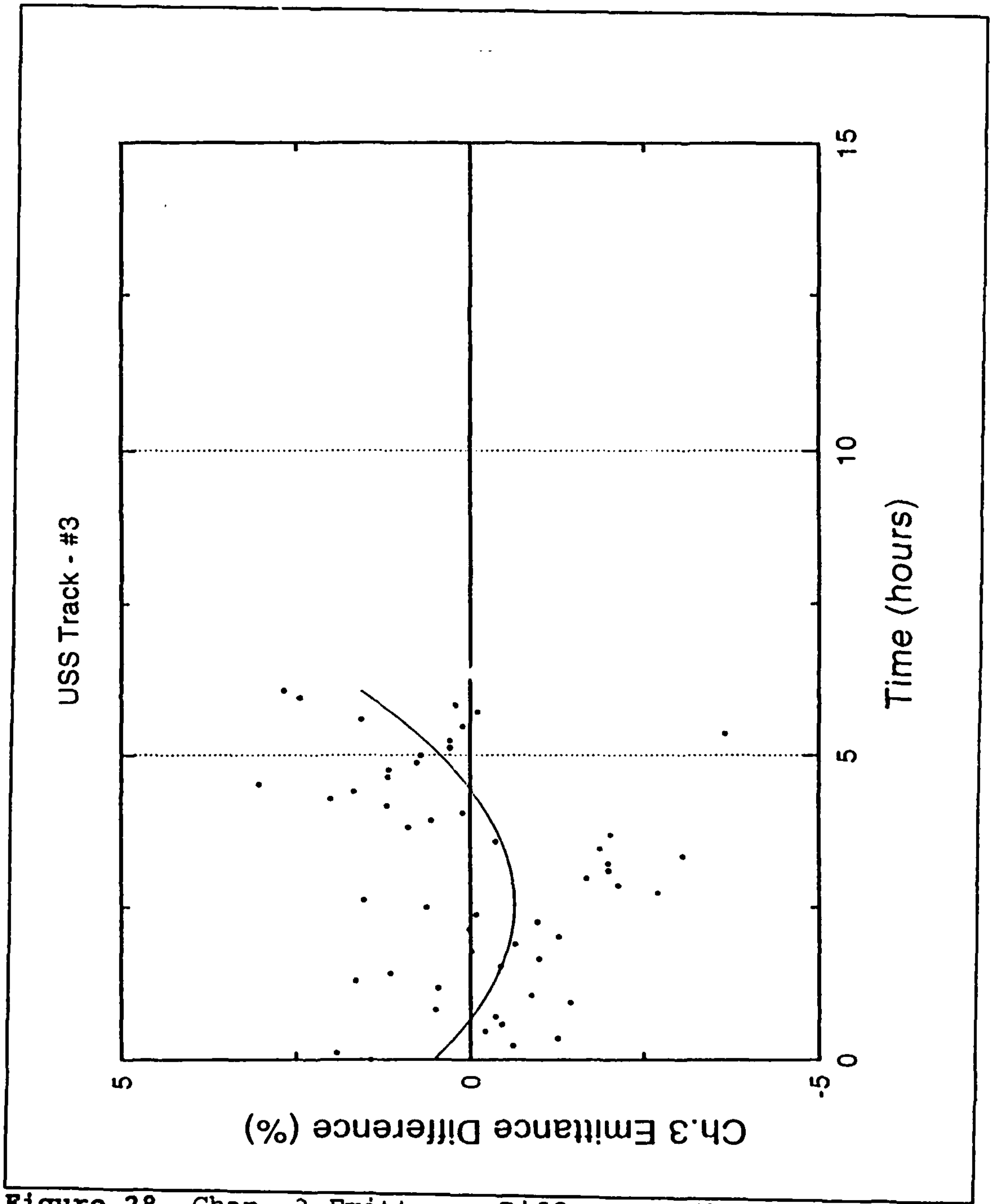

Figure 28. Chan. 3 Emittance Difference (%) for USS3.

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